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Liner Location Risk and Cost Analysis Model. Appendices

Pope-Reid Associates, Inc., St. Paul, MN

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OFFICE OF SOLID WASTE JANUARY 1985

DRAFT REPORT

LINER LOCATION RISK AND COST ANALYSIS MODEL

APPENDICES

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PREFACE

This volume contains the Appendices to the Liner Location Risk Analysis Model Draft Report, which was developed by a team of contractors under the direction of the U.S. Environmental Protection Agency, Office of Solid Waste, Economic Analysis Branch. These Appendices contain data, results and more detailed descriptions of the specific model components and methodologies that back up the presentation in the main volume.

LINER LOCATION RISK AND COST
ANALYSIS MODEL
DRAFT REPORT
APPENDICES

SUBMITTED TO THE
OFFICE OF SOLID WASTE
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APPENDIX A

FAILURE AND RELEASE SUBMODEL

1. EXECUTIVE SUMMARY

1.1 Objectives

The major objective in this Appendix, performed by Pope-Reid Associates is to provide estimates of the probability of system failure (release of leachate from the containment system) and leachate release from hypothetical facilities. A Monte Carlo simulation model was developed for this analysis. The facilities that were analyzed reflect two technologies (landfills and surface impoundments), a variety of design configurations (single-lined, double-lined, clay-lined, synthetic-lined, etc.), several climatic regimes (represented as net infiltration classes), and seven benchmark times. The latter represent the time periods over which the hypothetical facilities have aged and were selected to evaluate facility performance during pre-closure, post-closure, and post-care periods.

1.2 Methodology

The approach undertaken in the failure analysis included the following elements:

- Literature review of facility failure case studies;
- Review of RCRA design and operating requirements for land disposal facilities;
- Identification of initiating events and affected components;
- Evaluation of severity of failure event-component combinations;
- Development of failure scenarios using fault tree techniques;

- Quantification of failure scenario events;
- Development of a Monte Carlo simulation model; and
- Estimation of leachate and constituent budgets.

This approach underwent a peer review process by staff members of the Land Disposal Branch of OSW and OSW contractors.

1.3 Failure Scenarios

Review of guidance documents and case studies of actual land disposal facility failures resulted in the selection and study of the following types of system failure:

- Material Aging
- Consolidation
- Drum Failure
- Incompatible Waste/ Component Interaction
- Damage During Construction
- Improper Sealing
- Inadequate Liner Thickness
- Erosion due to Excess Run-On
- Rise of Groundwater Table
- Silting or Clogging of Collection System
- Flooding
- Inlet/Outlet Control Malfunction
- Improper Operation and Maintenance
- Catastrophic Releases
- Animal Burrowing

Fault-tree techniques were used to evaluate the frequency of occurrence of failure due to the above scenarios. Probabilities of individual events in the scenarios were based upon published data, upon engineering judgment and discussions during the peer review process.

1.4 Monte Carlo Simulation Model

The Monte Carlo simulation model developed under this study is based upon fault-tree analysis techniques. In this method of analysis, the most common types of system failure are broken down to combinations of component failures, the probabilities of these basic events are estimated, and a composite probability of the top event (release of leachate from the facility) is calculated using standard algebraic expressions involving the probabilities of the basic events.

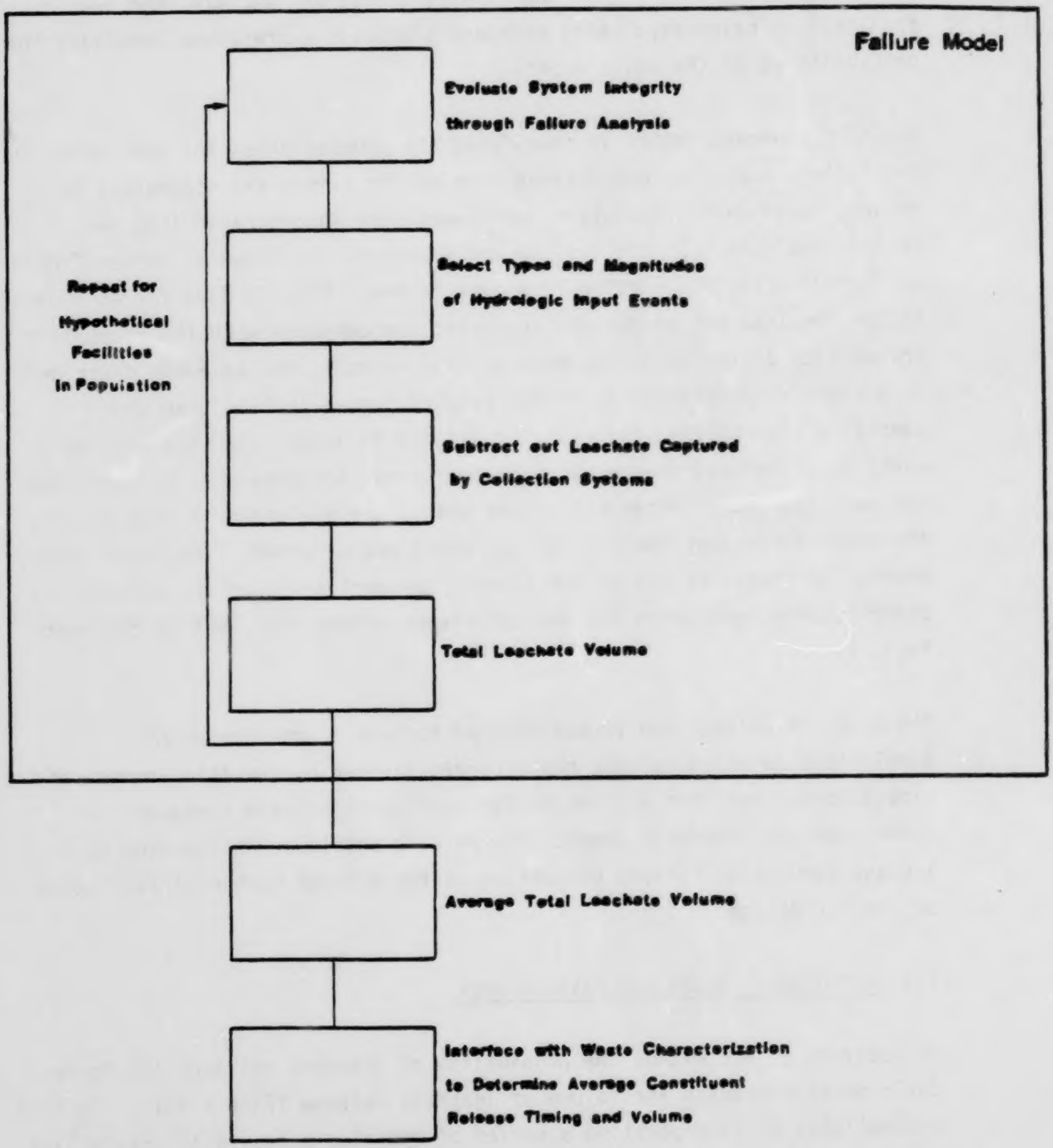
Due to the uncertainties in specifying the probabilities for the events in the failure scenarios and because some of the events are stochastic by nature, Monte Carlo simulation techniques were incorporated into the failure analysis. In the failure model numbers are drawn at random from a uniform distribution ranging from zero to one. This is done for each event in the combined set of failure scenarios and compared with the respective probability distribution parameters. For example, for an event described by a binomial distribution, if the sampled number is less than the specified probability, the event is assumed to occur. In this way, each event is either assigned a value of one (event has occurred) or zero (event has not occurred). After all of the events are evaluated in this manner, the model determines whether the top event has occurred. The model then resets the states of all of the events, re-samples all of the probability distributions, and tests for the occurrence of the top event in the next facility.

The model calculates the probability of failure as the number of simulations in which release has occurred divided by the total number of simulations. Runs for a given design configuration were conducted for seven separate benchmark times. The results should be interpreted as average cumulative failure probabilities for a large number of facilities of similar design.

1.5 Hydrologic Inputs and Mass Balance

In addition to estimating the probability of leachate release, the Monte Carlo model estimates the volume of leachate release (Figure A-1). This is accomplished by incorporating a series of hydrologic inputs in the failure scenarios and tracking them with a mass balance analysis. These hydrologic inputs include:

FIGURE A-1. ESTIMATION OF LEACHATE AND CONSTITUENT RELEASE VOLUMES


Failure Model
Evaluate System Integrity through Failure Analysis
Select Types and Magnitudes of Hydrologic Input Events
Repeat for Hypothetical Facilities in Population
Subtract out Leachate Captured by Collection Systems
Total Leachate Volume
Average Total Leachate Volume
Interface with Waste Characterization to Determine Average Constituent Release Timing and Volume

Reproduced from best available copy.

- Free liquids in waste
- Excessive run-off
- Flood waters
- Groundwater
- Infiltration from precipitation
- Slow or rapid leakage from surface impoundments

The leachate release volume is calculated by summing all the contributions to the leachate budget in a given simulation and subtracting out an amount which represents the leachate collected by drainage and leachate collection systems. The collection efficiencies of retrieval systems are varied in the failure model to reflect component failures. For example, the efficiency of a leachate collection system underlain by a liner might be 95 percent initially, but would be reduced by half if cracks were to develop in the liner.

An amount is also subtracted from the leachate budget to represent permanent storage capacity in clay liners. The result of a particular simulation is then the total volume of leachate released over a given benchmark period. The model calculates an average total release volume for all facilities that fail in a set of simulations.

1.6 Limitations

The results of the analysis must be tempered in light of the uncertainties in the data upon which the event probabilities and hydrologic input volumes are based. Even though readily available data concerning the reliability and performance of existing land disposal facilities were used, in many cases quantification of the failure events rested upon best engineering judgment. Because of this, actual probabilities may differ from estimated probabilities by one or two orders of magnitude. Experimentation with the failure model through a series of sensitivity analyses suggests that changes in certain critical event probabilities result in significant changes in failure rates and leachate release volumes. Nonetheless, scenarios run with very conservative estimates of liner longevity (for example, 150 years) still resulted in significant probabilities of failure within 50 to 100 years of operation. While more detailed information about component reliability from existing facilities is necessary to verify the model results in an absolute sense, the model is useful in providing a comparative evaluation of facility performance.

1.7 Key Findings

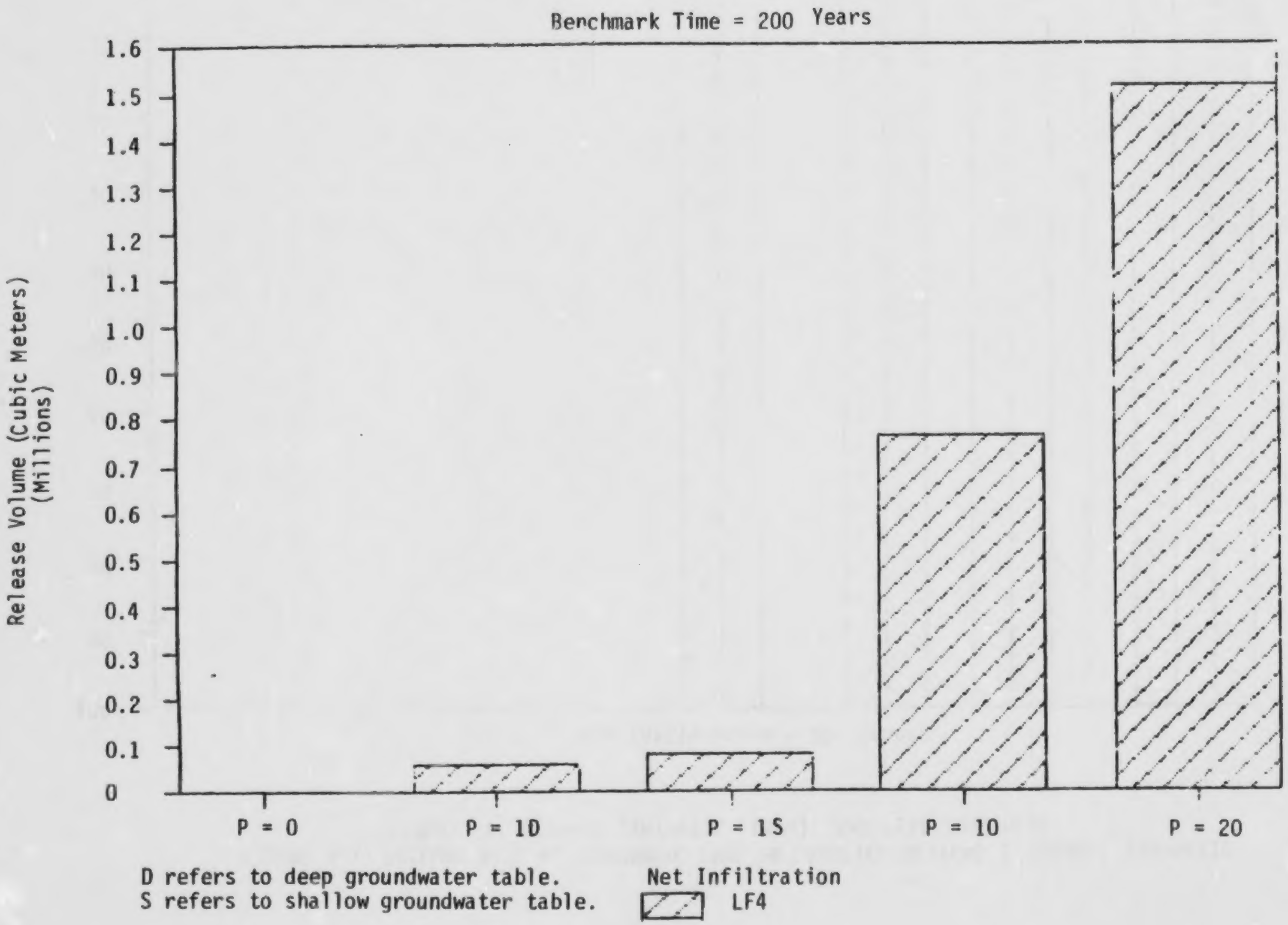
The results of the Monte Carlo model simulations suggest that failure probability and leachate release volume are affected by:

- Climate (net infiltration)
- Age of facility (benchmark time)
- Facility cost and level of technology (facility design)

In semi-arid and humid climatic regimes, nearly all facility designs experience failure within 200 years of operation. In arid regions (zero net infiltration), very few facilities fail. Leachate release increases for a given design and benchmark time as net infiltration increases as shown in Figure A-2 for landfill design IV (single clay liner).

Except in arid regions, facility failure rates and release volumes increase with benchmark time reflecting the time-dependent nature of component failures (Figures A-3 and A-4). Most designs attain high failure rates shortly after 50 years of operation. This suggests the importance of maintaining leachate collection and leachate detection systems in the post-closure period. Release rates may decrease with benchmark time in certain designs due to the "dilution" of relatively infrequent but large-magnitude failure rates with more frequent low-magnitude failures that occur during longer time periods. The latter are presumably associated with cover failures.

FIGURE A-2. RELEASE VOLUME vs NET INFILTRATION (IN INCHES) IN LANDFILL DESIGN IV (2 FT. THICK SINGLE CLAY LINER)



D refers to deep groundwater table.
S refers to shallow groundwater table.

FIGURE A-3. FAILURE RATE vs BENCHMARK TIME IN LANDFILL DESIGNS I (DOUBLE SYNTHETIC LINER), VI (SINGLE SYNTHETIC LINER), AND VIIA (UNLINED)

Net Infiltration = 20 Inches

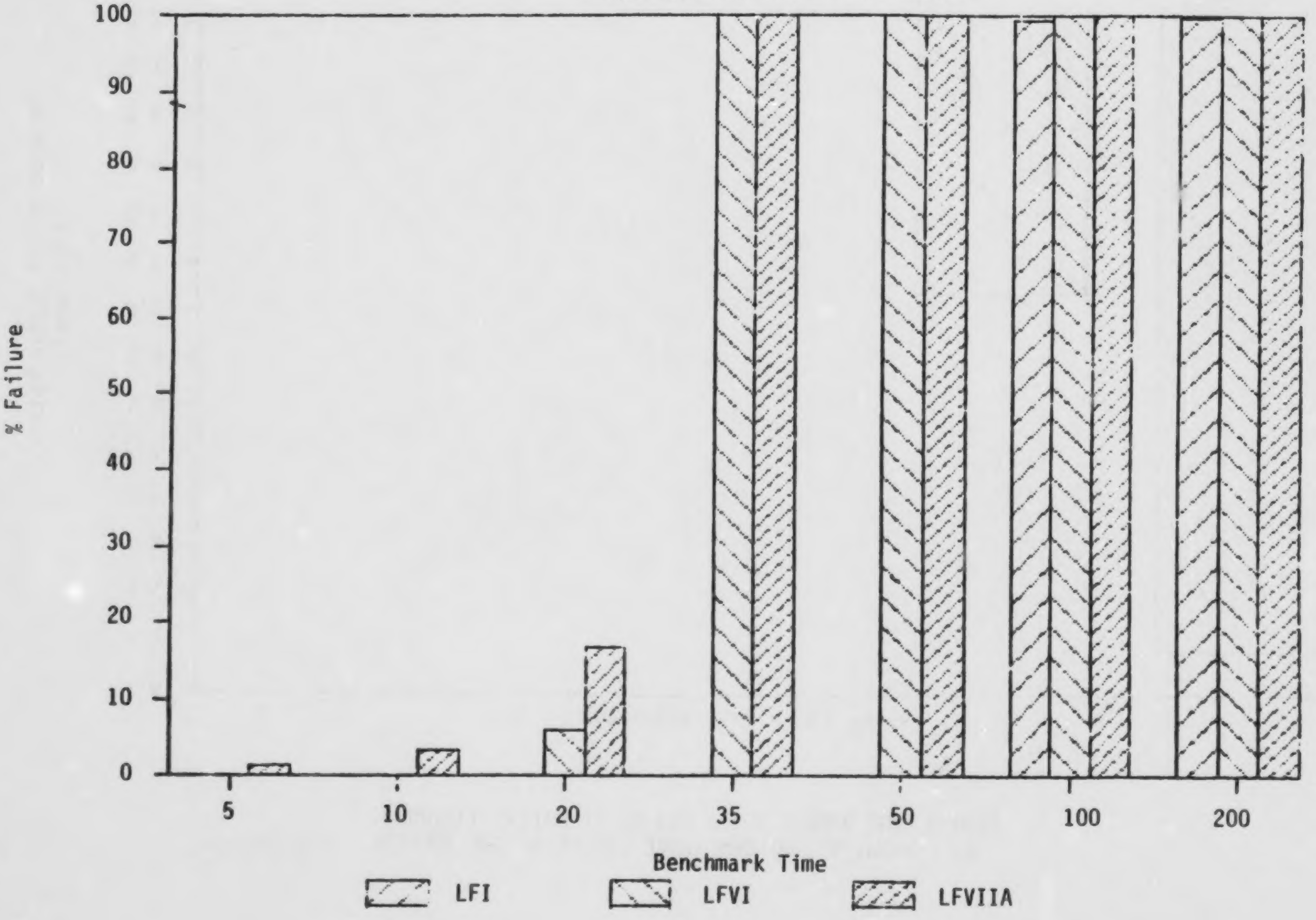
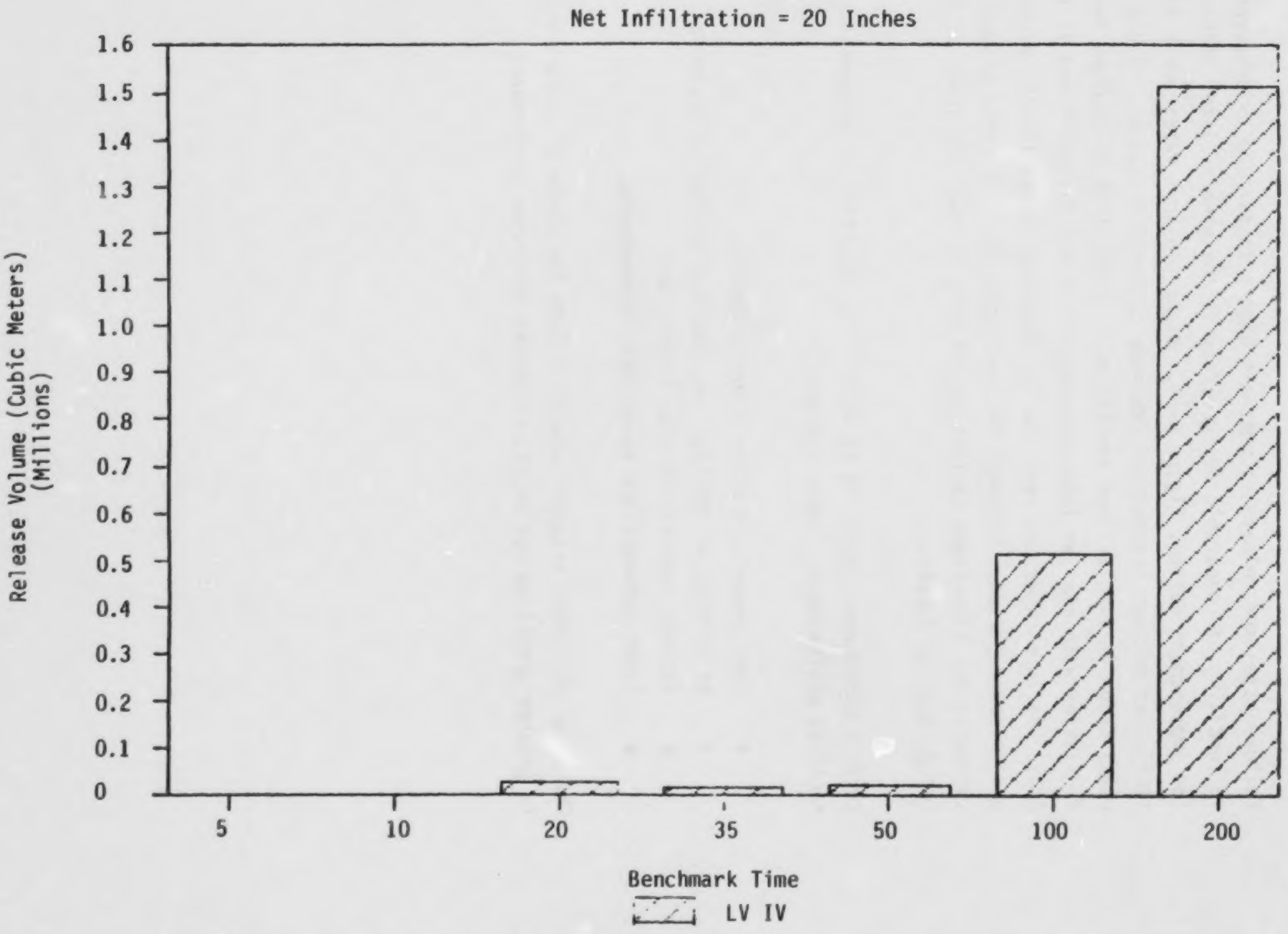


FIGURE A-4. RELEASE VOLUME vs BENCHMARK TIME IN LANDFILL DESIGN IV
(2 FT. THICK SINGLE CLAY LINER)



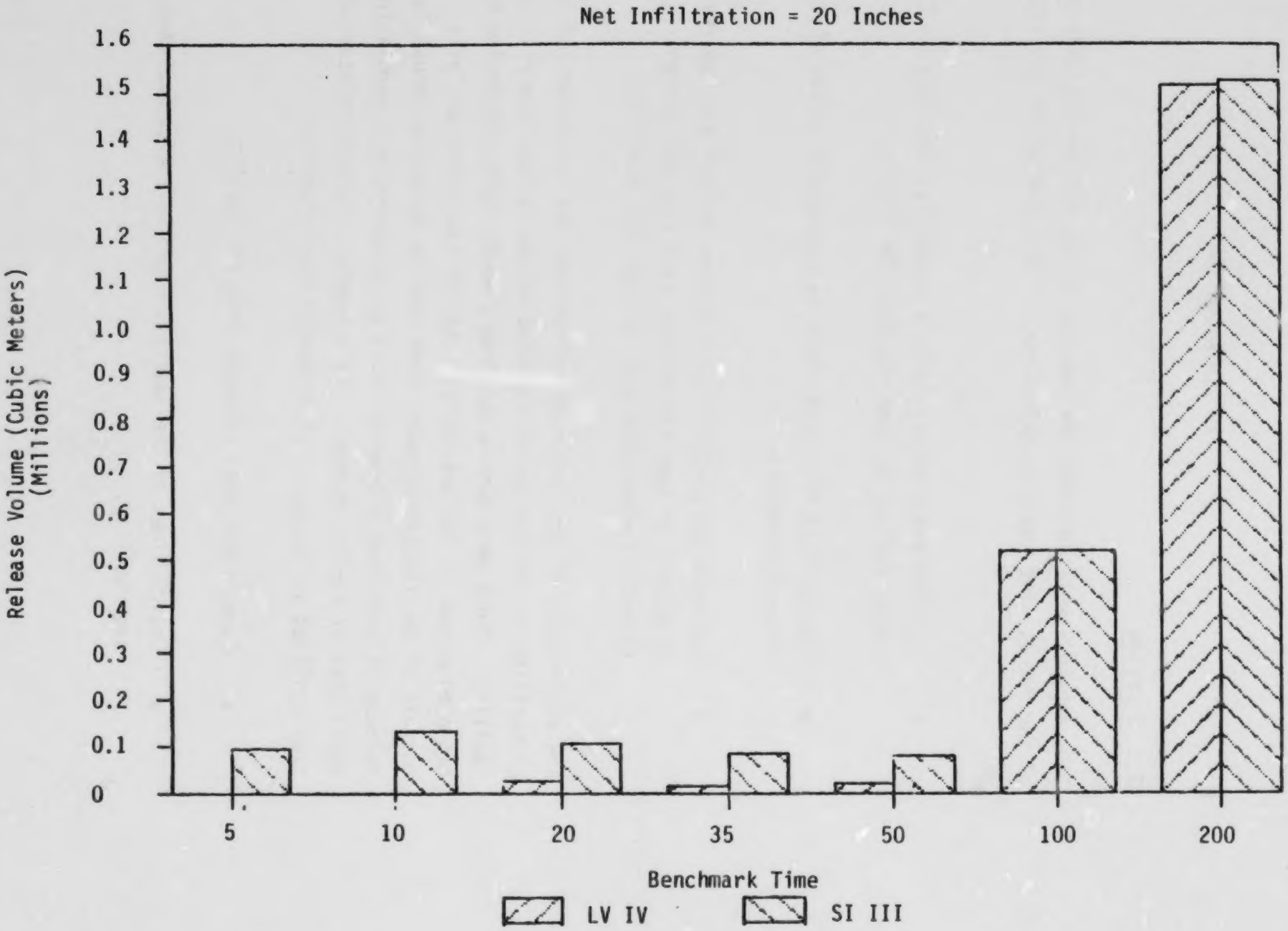
Failure rates and release volumes are higher in surface impoundments than in landfills of comparable design (despite the greater liner thickness in the impoundment design, Figure A-5). Higher failure rates occur in facilities without leachate or drainage collection systems. Higher failure rates occur in single-lined facilities in comparison to double-lined facilities with similar liner materials (compare designs I and VI in Figure A-3). Failure rates are very low for double-lined facilities through the post-closure period. Although failure rates are comparable between synthetic and clay-lined facilities, release volumes are lower in the latter type of facility.

Certain components appear to be especially important in determining overall facility performance. These include:

- containment and cover liner longevity;
- efficiency of drainage and leachate collection systems;
- storage capacity of clay liners; and
- liner permeability in surface impoundments.

The focus of future research should include the study of these components in greater detail to refine the estimates of system performance.

FIGURE A-5. RELEASE VOLUME vs BENCHMARK TIME FOR LANDFILL IV (2 FT. THICK SINGLE CLAY LINER) AND SURFACE IMPOUNDMENT III (7 FT. THICK CLAY LINER)



2. INTRODUCTION

2.1 Overview

This Appendix will describe the results of the failure analysis component of the Model. The specific objectives of this portion of the study were to:

- Identify and classify failure mechanisms that may contribute to system failure at land disposal facilities.
- Employ fault-tree techniques to generate a series of hypothetical failure scenarios.
- Estimate the probability of system failure and magnitude of attendant release for various land disposal designs in different climatic regions and over various time horizons.

The performance of the land disposal designs was characterized by a probability of failure and an expected volume of leachate released from the facility. These were determined from a Monte Carlo Simulation Model that employed a type of failure analysis called fault-tree analysis. The outputs of the simulation model were used to determine annual leachate release volumes from a generic facility representing a population of facilities of similar design. The schedule of annual release volumes were then utilized as inputs to other models that estimated:

- Constituent mass releases from the facility.
- Travel times of the leachate front in the unsaturated zone below the facility.

- Constituent concentrations in groundwater at exposure points in proximity to the facility.

- Risks to exposed populations.

These elements are more fully described in the other Appendices.

The remainder of this appendix will describe the steps used to develop the selected failure scenarios, quantify the probabilities and magnitudes of releases associated with the scenarios, and develop the Monte Carlo model used in the analysis. Assumptions and limitations of the analysis will also be described in the Methodology section.

A description of the model simulation parameters and results of the runs is included in the Results Section. Finally, a brief discussion of modifications to be made in future versions of the model will be included in the final section of this Appendix.

3. METHODOLOGY

3.1 Overview

The initial phase of the study involved specification of the components of the land disposal systems and the ways in which these components could fail. Design configurations were based upon a review of the Part 264 design and operating requirements for disposal facilities. Several variations upon the configurations, such as composite-lined or triple-lined containment liners were also considered. The alternative designs were based upon designs incorporated in other studies (Land Disposal Branch failure analysis) and from discussions with staff in the Economics Analysis Branch of OSW. Major system components included covers, drainage and leachate collection systems, leachate detection systems, containment liners, and berms.

Next, a variety of causes of component failure was considered. These ran the gamut from natural events (floods, seismic events) to poor operation and maintenance procedures (inadequate inspections) and component aging (the development of cracks in liners). These events were ranked according to their relative frequency of occurrence, degree of impact upon affected components, and upon total system performance. The evaluation method used to determine the severity of failure event-component combinations was based upon limited data from land disposal facility case studies and engineering analysis. The most important failure mechanisms indicated by this evaluation process were linked together using standard fault-tree techniques.

Fault-tree analysis is a systematic approach to evaluate the causes and frequency of technologic failures. Using this technique, a series of failure scenarios leading to the generation and release of leachate from disposal facilities was developed. These were evaluated with the aid of a computerized Monte Carlo Simulation model to estimate the probability and magnitude of release over time from a variety of disposal designs in different climatic settings.

The following parts of the methodology section will describe these elements in greater detail and document the approaches and assumptions used to develop the disposal facility failure and release estimates.

3.1.1 Disposal Facility Components and Operating Requirements

Conceptual designs were developed for two hazardous waste land disposal technologies, landfills and surface impoundments, to facilitate the identification of failure mechanisms affecting these technologies. This section will briefly describe the designs selected for analysis.

The conceptual designs were based upon two sources: The design and operating requirements contained in the July 26, 1982 RCRA land disposal regulations and (2) a description of engineering design specification specified in a February 1983 memorandum from the Land Disposal Branch (OSW), entitled "Evaluation of Land Disposal Facility Technologies and Integration of Waste of Waste/Environmental/Technology Characteristics to Produce Facility Profiles."

The latter source describes the Land Disposal Branch's approach to the performance evaluation of design alternatives to the 264 requirements for disposal facilities. To facilitate the comparison of results from this study with those of the Land Disposal Branch study, the same facility configurations in terms of geometry (rectangular cells with vertical side slopes), area (approximately 25 acres) cover and containment slopes, and leachate tile spacing were used in this study. Additional design configurations, including triple-lined facilities and unlined facilities, were included at the request of EPA staff.

Major components of the facility designs analyzed in this study are defined and summarized in Figures A-6 and A-6a-b. Detailed design specifications are included in Tables A-1 and A-2. It should be mentioned that not all simulations were run for the landfill and surface impoundment design configurations are listed in these tables.

3.1.2 Literature Review of Failure Mechanisms

An extensive review of literature documenting disposal facility failures was conducted to determine the relative frequency of failure mechanisms, the timing of failures in terms of the operational phases at disposal facilities, and the impacts of component failures on other components within facilities.

Sources for the literature review included:

- Computer data bases (Compendex and Pollution Abstracts)
- Hazardous waste, solid waste, and groundwater monitoring periodicals
- Symposia proceedings on uncontrolled hazardous waste sites, EPA research, and geomembrane performance
- EPA hazardous waste technical resource documents
- Case studies of remedial actions published by EPA
- Other documents concerning hazardous waste and remedial actions published by state agencies

The specific references reviewed in the literature search are included in the bibliography at the end of this report.

FIGURE A-6

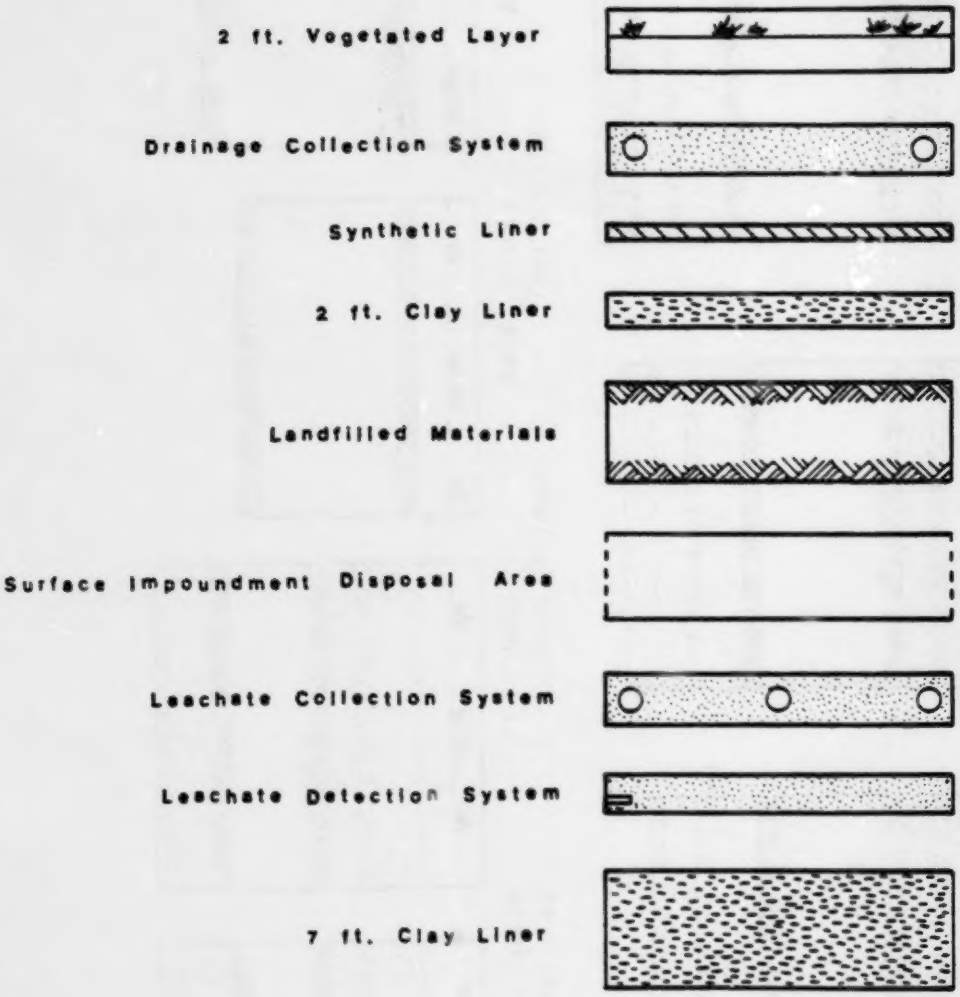

2 ft. Vegetated Layer
Drainage Collection System
Synthetic Liner
2 ft. Clay Liner
Landfilled Materials
Surface Impoundment Disposal Area
Leachate Collection System
Leachate Detection System
7 ft. Clay Liner

FIGURE A-6a DESIGN CONFIGURATIONS FOR LANDFILLS

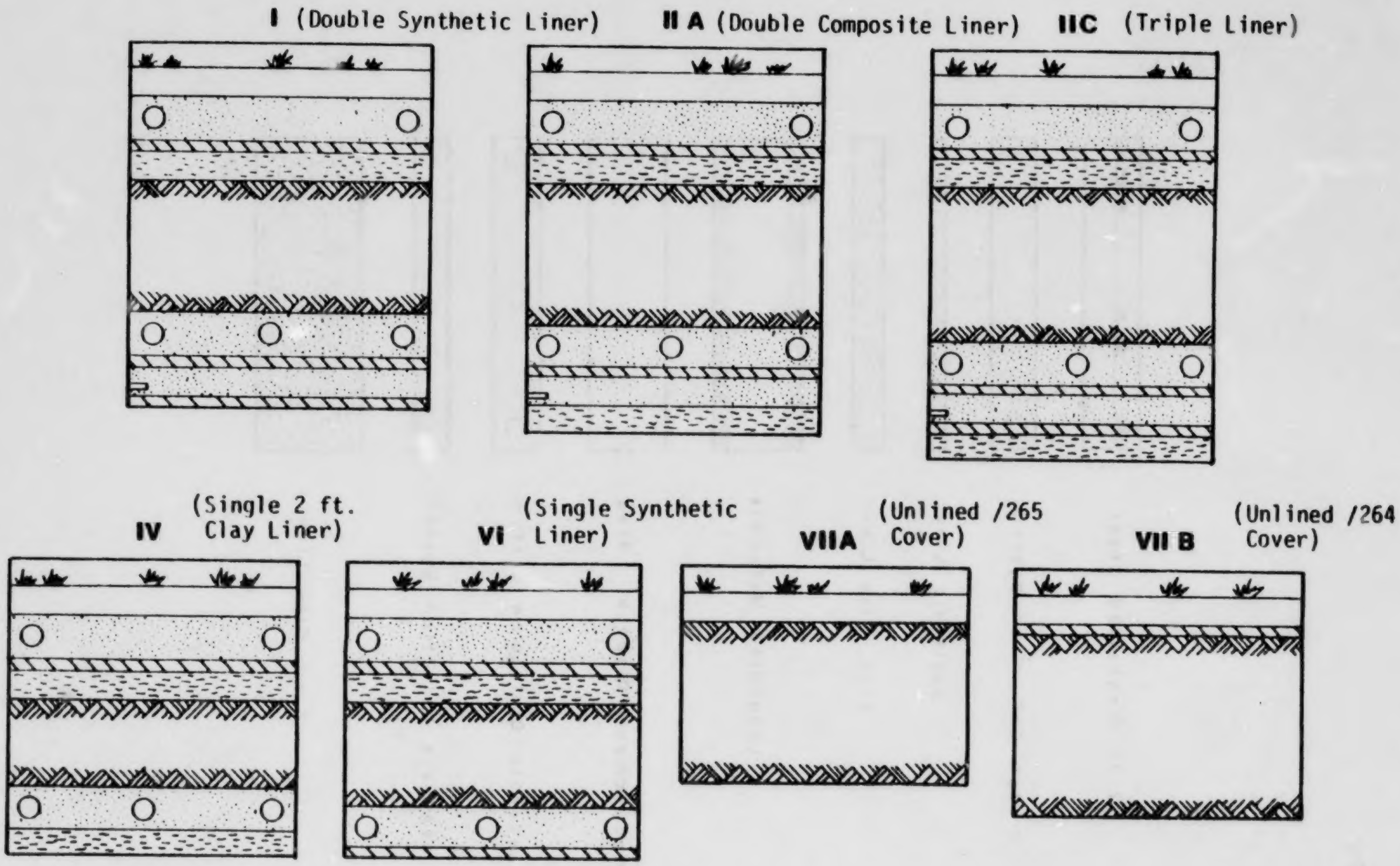

I (Double Synthetic Liner)
II A (Double Composite Liner)
IIC (Triple Liner)
IV (Single 2 ft. Clay Liner)
VI (Single Synthetic Liner)
VIIA (Unlined /265 Cover)
VII B (Unlined /264 Cover)

FIGURE A-6b DESIGN CONFIGURATIONS FOR SURFACE IMPOUNDMENTS

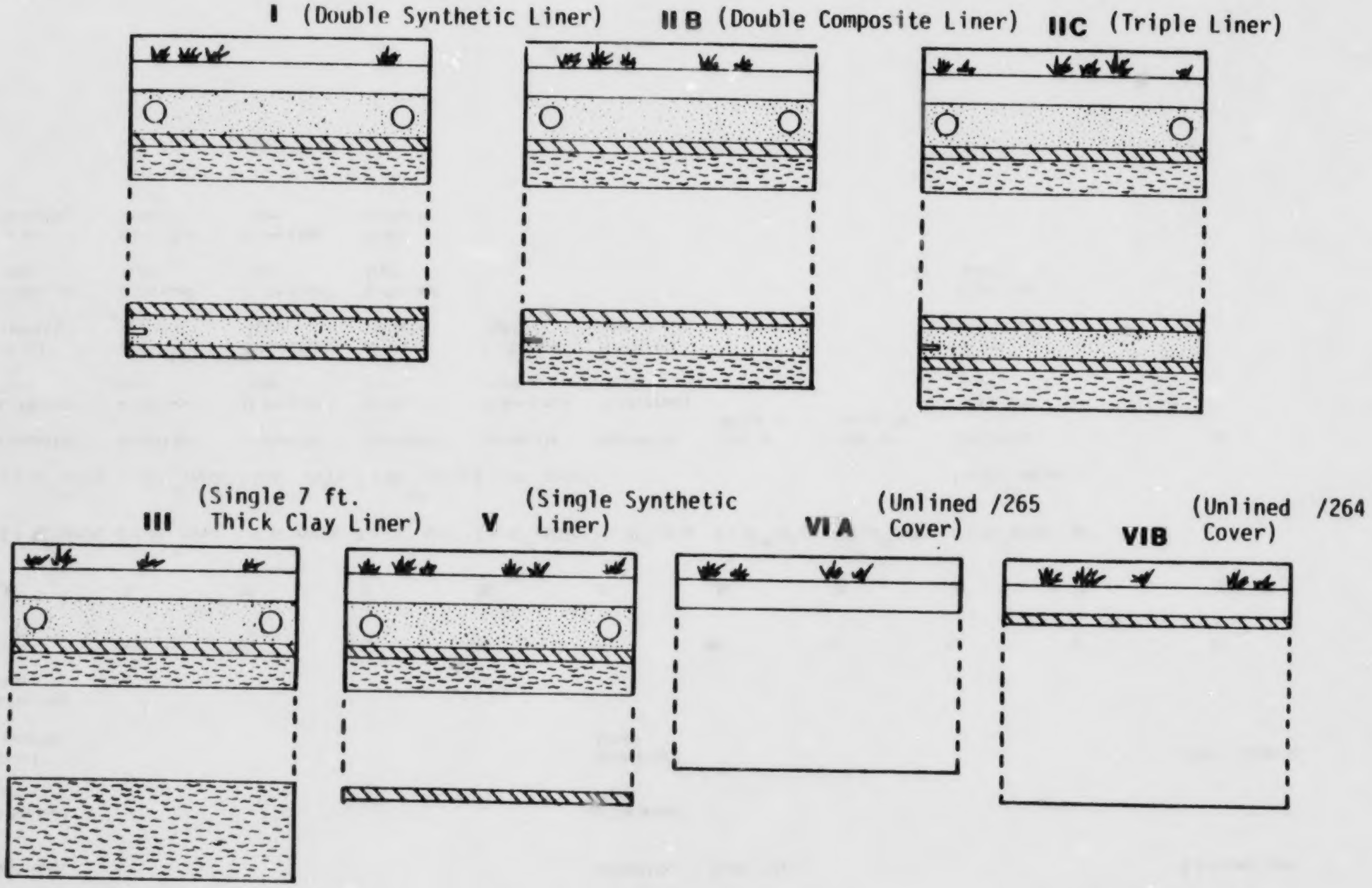

I (Double Synthetic Liner)
II B (Double Composite Liner)
IIC (Triple Liner)
III (Single 7 ft. Thick Clay Liner)
V (Single Synthetic Liner)
VI A (Unlined Cover)
/265
VIB (Unlined Cover)
/264

TABLE A-1. LINED LANDFILLS

	Design Scenarios										
Design Components	I (Double Lined)	IIA (Double Lined)	IIB (Double Lined)	IIC (Triple Lined)	III (Single Lined)	IV (Single Lined)	VA (Single Lined)	VB (Single Lined)	VI (Single Lined)	VIIA (Unlined)	VIIB (Unlined/266 Cover)
Final Cover	0.61m vegetated layer Geotextile 0.30m sand layer 20 mil synthetic 0.61m clay layer	Same as Design I	Same as Design I	Same as Design I	Same as Design I	0.61m vegetated layer Geotextile 0.30m gravel layer 0.61m clay layer	0.30m vegetated layer 0.61m clay	Same as Design VA	Same as Design I	.61m vegetated layer	.61m vegetated layer 0.3 m sand layer 20 mil synthetic
Drainage Tiles	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	NO
Final Cover Slope	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Clay Permeability	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-6} cm/sec	1×10^{-5} cm/sec	1×10^{-7} cm/sec	No	
Synthetic Permeability	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec				1×10^{-12} cm/sec		
Containment System	Geotextile 0.30m sand layer 36 mil synthetic 0.30m sand layer 36 mil synthetic	Geotextile 0.30m sand layer 36 mil synthetic 0.30m sand layer 0.61m clay layer	Geotextile 0.30m gravel layer 0.61m clay layer 0.30m gravel layer 0.61m clay layer	Geotextile 0.30m sand layer 36 mil synthetic 0.30m sand layer 36 mil synthetic	Geotextile 0.30m gravel layer 2.13m clay layer	Geotextile 0.30m gravel layer 0.61m clay layer	Same as Design IV	Same as Design IV	Geotextile 0.30m sand layer 36 mil synthetic 0.15m sand layer		NO

TABLE A-1. LINED LANDFILLS (Continued)

	Design Scenarios										
Design Components	I (Double Lined)	IIA (Double Lined)	IIB (Double Lined)	IIC (Triple Lined)	III (Single Lined)	IV (Single Lined)	VA (Single Lined)	VB (Single Lined)	VI (Single Lined)	VIIA (Unlined)	VIIB (Unlined/266 Cover)
	0.15m sand layer			0.15m sand layer 0.61m clay layer							
Containment System Side Slope (run:rise)	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1		
Containment System Bottom Slope	2%	2%	2%	2%	2%	2%	2%	2%	2%		
Leachate Collection System	Drainage tile system with 15.25m spacing	Same as Design I	Same as Design I	Same as Design I	Same as Design I	Drainage tile system with 30.48m spacing	Same as Design IV	Same as Design IV	Same as Design I		
Leachate Detection System	Drainage tile system with 15.25m spacing	Same as Design I	Same as Design I	Same as Design I	None	None	None	None	None		

TABLE A-2. LINED DISPOSAL SURFACE IMPOUNDMENTS

	Design Scenarios										
Design Components	I (Double Lined)	IIA (Double Lined)	IIB (Double Lined)	IIC (Triple Lined)	III (Single Lined)	IVA (Single Lined)	IVB (Single Lined)	IVC (Single Lined)	V (Single Lined)	VIA (Unlined)	VIB (Unlined/265 Cover)
Final Cover	0.61m vegetated layer Geotextile 0.30m sand layer 20 mil synthetic 0.61m clay layer	Same as Design I	Same as Design I	Same as Design I	Same as Design I	0.61m vegetated layer Geotextile 0.30m gravel layer 0.61m clay layer	Same as Design IVA	Same as Design IVA	Same as Design I	.61m vegetated layer	.61m vegetated layer 0.30m sand layer 20 mil synthetic
Drainage Tiles	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Final Cover Slope	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Clay Permeability	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-7} cm/sec	1×10^{-6} cm/sec	1×10^{-5} cm/sec	1×10^{-7} cm/sec		
Synthetic Permeability	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec	1×10^{-12} cm/sec				1×10^{-12} cm/sec		
Containment System	0.15m soil layer 36 mil synthetic Geotextile 0.30m sand layer	0.15m soil layer 36 mil synthetic Geotextile 0.30m sand layer	0.61m clay layer Geotextile 0.30m gravel layer 0.61m clay layer	0.15m soil layer 36 mil synthetic Geotextile 0.30m sand layer	2.13m clay layer	0.61m clay layer	Same as Design IVA	Same as Design IVA	0.15m soil layer 36 mil synthetic 0.15m sand layer	No	No

FIGURE A-2. LINED DISPOSAL SURFACE IMPOUNDMENTS (Continued)

Design Scenarios

Design Components	I (Double Lined)	IIA (Double Lined)	IIB (Double Lined)	IIC (Triple Lined)	III (Single Lined)	IVA (Single Lined)	IVB (Single Lined)	IVC (Single Lined)	V (Single Lined)	VIA (Unlined)	VIB (Unlined/265 Cover)
	36 mil synthetic	0.61m clay layer		36 mil synthetic							
	0.15m sand layer			0.15m sand layer							
				0.61m clay layer							
Containment System Side Slope (run:rise)	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1	0.5:1		
Containment System Bottom Slope	2%	2%	2%	2%	2%	2%	2%	2%	2%		
Leachate Collection System	None	None	None	None	None	None	None	None	None		
Leachate Detection System	Drainage tile system with 15.25m spacing	Same as Design I	Same as Design I	Same as Design I	None	None	None	None	None		

A summary of failure cases elicited from the literature review is shown in Table A-3. Data in Table A-3 include the failure mode, cause of the failure or initiating event, the major component that failed, impacts to other components (such as overloading of leachate collection system in response to excessive infiltration), timing of failure (pre- or post-closure), and type of facility at which the failure occurred. The failure mechanisms listed in Table A-3 were further classified into major categories of failure, including natural events, location - specific events, operation and maintenance, improper construction techniques, and improper design. Despite the fact that most of the case studies involve facilities constructed prior to promulgation of the RCRA regulations, at least some of the facilities represent 264 designs. The case studies do provide a list of potential failure mechanisms which might typically be encountered at existing and proposed waste disposal facilities. Furthermore, they provide a framework for development of the failure scenarios, combinations of failure mechanisms that lead to system failure. In some instances, the case studies also provide information about the time-frame over which a particular component failure occurs; for example the time for drum corrosion or for cover subsidence to occur.

The most common types of failures included in the summary table were:

- leaks in liners or seepage from unlined facilities
- infiltration of precipitation into trenches
- breach of dikes
- violent reaction resulting from contact of incompatable wastes
- rupture of drums
- overflow of leachate from closed facilities (bathtub effect)

Failures were generally the result of improper design, construction or maintenance activities.

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Infiltration into trenches and contamination of nearby stream	Subsidence of cover, improper maintenance	4-8 foot thick cover of natural soils	None indicated	During trench closure	Low level radioactive waste landfill
Infiltration into trenches	Subsidence of cover, improper maintenance	Cover	None indicated	Either during the active life or trench closure	Low level radioactive waste landfill
Infiltration in trenches	Subsidence of cover, improper maintenance	Cover	None indicated	Either during the active life or trench closure	Low level radioactive waste landfill
Seepage of radioactive leachate from cover	Infiltration due to cracks and holes in cover, improper design or maintenance	Trench cover	Leachate collection system overloaded	4-5 years after trench closure	Secure landfill
Major fires, infiltration into trenches, high leachate levels	Differential settlement desiccation cracks, and erosion leading to infiltration, improper design, construction or operation	Cover	Leachate collection system and liners are functioning properly	During trench closure, 5-10 years after start-up	Secure landfill
Drums of acids and solvents submerged in rainwater in a burial pit	Improper design and maintenance	Run-on/run-off control, leachate collection system	None indicated	During active life	Landfill
Breakouts from lagoon to nearby stream, seepage to groundwater	Overtopping of berm, improper maintenance	Berms	Monitoring wells functioning properly	During active life	Lagoon

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Liquid wastes entered nearby stream	Brench of earthen dike, improper construction	Dike	None indicated	During active life	Lagoon
Contamination of groundwater and surface water, fish kills, cattle sickness	Holes breached in dam by run-off, improper construction, and maintenance	Dam	None indicated	Not indicated	Lagoon
Overtopping of levee, spill of PCB, lead-contaminated oil into soil and nearby creek	Rupture of levee due to heavy rainfall, improper construction and maintenance	Levees	None indicated	Problem for many years	Pit
Seepage through berms to surface water, subsurface seepage in bedrock fractures	Improper construction, improper location	Berms	None indicated	Not indicated	Surface impoundment
Rupturing of levees, spill of liquid wastes to nearby creek	Perhaps due to excess precipitation or groundwater through-flow; improper location	Levees	None indicated	During active life	Pits
Liner rupture due to formation of sinkhole	Natural event or improper location	Clay liner	None indicated	Assume during operating life	Sewage lagoon
Leak in liner causing groundwater contamination	Perhaps slow leakage through liner	Bentonite liner	Monitoring wells functioning properly	Not indicated	Sewage treatment lagoon
Leachate detected between containment liners	Either improper placement of liner in trench or break in liner caused by truck traffic, improper construction or operation	18" clay primary liner	Leachate detection system functioning properly and presume secondary liner functioning properly	During active life (8 months after beginning operation)	Chemical landfill

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Liquid pumped from leak detection layer between containment liners	Either leak in primary liner or rainwater trapped between liners during construction, improper installation or operation	30-mil Hypalon primary liner	Leak detection sumps functioning properly and presume secondary liner functioning properly	During active life (2 months after beginning operation)	Landfill
Leachate detected between containment liners	Either leak in primary liner or rainwater trapped between liners during construction, improper installation or operation	30-mil PVC primary liner	Leak detection sumps functioning properly and presume secondary liner functioning properly	During active life (a few months after beginning operation)	Landfill
Leachate detected between containment liners	Leak in primary liners	30-mil PVC primary liner	Leak detectors functioning properly	During active life (a few months after beginning operation)	Secure landfill
Overflow of wastewater from lagoon	Improper design (undersized facility)	Presume the liner	None indicated	During active life	Lagoon
Seepage from lagoon into groundwater	Slow seepage through liner(?)	Clay liner	None indicated	Not indicated	Lagoon
Seepage from impoundment into groundwater	Slow seepage through liner(?)	Liner	None indicated	Not indicated	Surface impoundment
Seepage from lagoon into groundwater	Improper operation, maintenance, and design, improper location (water table lies within impoundment)	Asphalt liner	None indicated	Not indicated	Lagoon
Containment indicated by monitoring wells	Drums that either broke open during landfilling or deteriorated, improper operation	Closed cell	Groundwater monitoring wells functioning properly	During closure	Hazardous waste

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Elevated leachate levels in collection system	Clogged standpipes and inappropriate pumps and piping, improper design	Leachate collection system	None indicated	During closure	Secure landfill
Vegetation kills, methane concentrations in nearby homes	Lateral gas migration, improper design	Fill area	None indicated	Not indicated	Landfill
Flash fires	Lateral gas migration, improper design	Fill area	None indicated	Not indicated	Landfill
Odors and vegetation kills	Lateral gas migration, improper design	Fill area	None indicated	Not indicated	Landfill
Vegetation kills, fires, odors	Lateral gas migration, improper design	Fill area	None indicated	During active life	Landfill
Vegetation kill in peach orchard	Lateral gas migration, improper design	Fill area	None indicated	Not indicated	Landfill
Fumes of HCl resulting from disposal of incompatible wastes, rupture of drums	Improper operation	Soil cover	None indicated	During active life (12 months after disposal)	Hazardous waste landfill
Placement of incompatible wastes resulting in fire	Incorrect labeling of wastes, improper operation	Fill area	None indicated	Not indicated	Sanitary landfill
Placement of incompatible wastes resulting in generation of toxic fumes	Improper operation	Active fill area	None indicated	During active life	Sanitary landfill

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Small fires resulting from mixtures of incompatible wastes	Improper operation	Active fill area	None indicated	During active life	Landfill
Ignition of ruptured barrelled wastes, mixture of incompatible wastes	Inadequate inventory control, improper operation	Active fill area	None indicated	During active life	Landfill
Ignition of large fire resulting from mixture of incompatible wastes, leaky containers	Failure to apply daily cover, improper operation	Active fill area	None indicated	During active life	Landfill
Release of toxic gas resulting from mixture of incompatible wastes	Improper operation	Active fill area	None indicated	During active life	Landfill
Release of toxic gas resulting from mixture of incompatible wastes	Improper operation	Active fill area	None indicated	During active life	Sanitary landfill
Release of toxic gas resulting from mixture of incompatible wastes	Improper operation	Active fill area	None indicated	During active life	Sanitary landfill
Rupture of drums and leakage of liquid hydro-carbons	Improper construction and operation	Liner and active fill area	Monitoring wells functioning properly	Shortly after closure	Municipal landfill

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Leakage of leachate from containment system, elevated lead concentrations found in monitoring wells within 50 feet of landfill	Unknown	Liner (3 foot recompacted clay)	None indicated	Unknown	1 3/4 acre landfill for disposal of bag-house dust
Leachate detected in leachate detection system between two recompacted clay liners	Not determined	Upper clay liner (18"-25" recompacted clay)	None indicated	Within one year after start of operations	Landfill for sewage treatment plant sludge and chemical wastes from lime slaker operation
Detection of elevated tolune levels in monitoring wells	Perhaps upward seepage of groundwater just below clay layer, improper design	Un-compacted 17 foot in-situ clay layer	None indicated	Organics detected during first quarter of monitoring sampling (10 years after start up.	Ash disposal lagoons (wastes include residue from concentration of liquid wastes and sewage sludge.
Contamination of subgrade materials and groundwater by organics and breach of 2 clay-lined ponds in winter	Excess leakage from unlined impoundment, improper design, unknown cause for breach of other ponds.	Seepage from bottom of unlined impoundment, breach of side slopes of 2 ponds (2 foot thick blue clay)	Overloading of leachate collection system in unlined impoundment	Soon after installation of underdrain in unlined impoundment and within a year of construction of clay lined ponds	Solvent recycling facility with surface impoundments for still bottom wastes
Mixture of incompatible wastes, loss of volatiles to atmosphere	Haphazard drum disposal leading to drum ruptures, improper operation	Fill area	None indicated	During active life	Commercial hazardous waste landfill

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Rupture of containers in unlined trenches	Unknown	Fill area	None indicated	During active life	Unlined trenches at university disposal facility
Overflowing earthen pond, leachate bubbling out of ground, overflow and bypass of leachate collection tanks	Ponding due to inadequate grading and covering, erosion of berm, improper operation	Cover, pond berm	Overloading of leachate collection tanks	During active life and post-closure	55-acre solid waste landfill which contains some hazardous waste
Fire accompanied by dense smoke and odors, leakage of unburied drums	Drum of contaminated gasoline spilled by a bulldozer caught fire, spontaneous composition of drummed chemicals, improper operation	Fill area	None indicated	During active life	Commercial dump
Soil contamination by paint and ink solvents, seepage of chemicals into a nearby stream	Conversion of drums within an 11-year period, improper operation	Storage area	None indicated	After closure of facility	Solvent reclamation facility
Seepage of contaminated rainwater through cover vents	Fumes from waste disintegrated the cover allowing infiltration to fill area, incompatible waste	4 mil poly cover over 6" of clay	None indicated	Within 6 weeks of closure	Temporary EPA remedial action landfill
Contamination of soils and a nearby creek	Erosion of berms due to excess precipitation and ORV traffic, improper maintenance	Levees and berms	None indicated	Unknown	Waste oil pits

TABLE A-3. A SUMMARY OF FAILURE MECHANISMS AND COMPONENTS AFFECTED AT LAND DISPOSAL FACILITIES (continued)

Failure Mode	Cause of Failure	Major Component that Failed	Spin-Off Effects on Other Components	Timing	Type of Facility
Tearing of liners in evaporation ponds	Shrinkage of liner due to high heat and acidic conditions, material aging	20 and 40 mil PVC liners	None indicated	During active life (within 3 years after installation)	Uranium mine tailings impoundments
Tearing of synthetic membranes	Mechanical damage to membranes, one occurred during cleaning operations, improper operation.	20 mil PE liners	None indicated	During active life (within 5 and 6 years of installation, respectively)	Ore tailings dump and fertilizer effluent dam
Leakage of concentrated brine from storage pond	Desiccation and weathering of clays, freeze/flaw, rodent burrowing, exposure to concentrated brine, silt layers, improper design and maintenance	.75-1.50 m thick clay liner	None indicated	During active life (within 4 years of startup)	Brine storage pond

3.1.3 Frequencies of Failure Events

The probability of system failure is a composite function of individual component failure probabilities. Unfortunately for the purpose of estimating failure at permitted facilities, facilities designed and constructed under the 264 regulations have not been in existence for very long and are relatively few in number. Consequently, reliability estimates for disposal facility components are not generally available.

In some cases, laboratory and field tests have been conducted by EPA to evaluate the short-term performance of components over time (for example liner exposure tests conducted by Haxo and others). Other studies have been conducted by liner manufacturers to evaluate the integrity of liner materials under simulated actual operating conditions. Some types of synthetic membranes have been commercialized for 20 to 50 years. However, their use has primarily been in water impoundment applications. Proceedings from a recent symposium on geomembranes and an EPA-sponsored study of expected lifetime for synthetic liners and caps (ADL, 1983) describe several such studies.

Failure analysis has been applied in other contexts, such as the study of nuclear reactors and chemical processing plants. An example is the Wash-1400 study conducted by the Nuclear Regulatory Commission to assess risks in nuclear power plants. Thirty separate data sources were analyzed and evaluated to provide upper- and lower-bound estimates of failure probabilities for various components, such as pumps, valves, and flanges. Although some of these components would have analogous counterparts in disposal facilities, design specifications for the reactor components in disposal facilities, design specifications for the reactor components might be expected to be more stringent. Hence the component failure rates, if applied to disposal facilities, should be considered as lower bound estimates. General error rates for operators and inspections are also provided in the Wash-1400 study. These estimates were based on techniques developed at Sandia Laboratories.

Other pertinent data were available for a series of field investigations conducted by the NRC of low-level radioactive burial sites. These studies focused on the development of cracks in soil covers, the resulting overflow of disposal trenches from accelerated infiltration, and the deterioration of buried barrels.

Certain component failure rates can also be estimated indirectly by determining the frequency of occurrence of natural processes which act as initiating events. For example, the occurrence of catastrophic failures resulting from seismic events can be estimated by considering the recurrence interval for large-magnitude seismic events in susceptible areas of the country. Recurrence intervals for devastating earthquakes in the San Francisco and Los Angeles areas has been estimated to range from 100-125 years. Estimates for the occurrence of such location - specific events also presumes that a facility is located in an area susceptible to the event, otherwise a facility would have vanishingly small probabilities of failure from these events.

There are two approaches to handling location - specific events. The first assumes a priori that a facility is either in or out of an area susceptible to a particular event (i.e., earthquake zones, karst areas, or floodplains). Maps delineating such zones have been developed for a variety of geological hazards by USGS, SCS, and other agencies. If the facility is in a hazard zone, then the probability of failure is simply related to the recurrence interval of the event in question. For example, 100-year flood event has a probability of occurrence in any given year of 1/100 or 0.01.

A second approach (and the one selected for this analysis is that the probability of occurrence is the product of the probabilities of (1) a randomly selected facility lying within a hazard zone and (2) the probability of the event occurring. The first probability is calculated by taking the number of facilities in the regulated community located within a hazard zone and dividing by the total number of facilities. If the facilities are assumed, as a first approximation, to be randomly distributed throughout the country, the probability is given by the fraction of the area of the country occupied by a particular hazard zone.

Estimated component lifetimes, component failure rates and frequency of occurrence for several natural processes (that may initiate component failures) are listed in Table A-4. The data are subdivided into three reliability categories corresponding to the way in which they were originally cited. As discussed in a later section, the reliability data and frequency of occurrence estimates were used to generate the event probability distributions used in the simulation model.

3.1.4 Severity of Component Failures

Because of the large number of possible combinations of events leading to system failure, it was necessary to focus on the most critical failure pathways in the development of the simulation model and screen out less pertinent ones. In effect, very low probability events were eliminated from consideration. To facilitate the selection of the events comprising the failure scenarios, a method of ranking the severity and relative probability of event-component combinations was developed. Severity in the context of this study involved several factors, including ease of detecting the failure, size of release directly caused by the failure (and hence remedial cost), cost of replacing failed components, and the magnitude of spin-off effects of failure components to other "downstream" components.

The first step in the evaluation process involved the tabulation of specific failure mechanisms. These were grouped according to the major failure categories described previously. The failure mechanisms are listed opposite major system components in Tables A-5 and A-6 for landfill and surface impoundment facilities. Note that the evaluation of the failure mechanisms in terms of severity is only valid in the context of effects on the function of a given component or group of components.

The next step in the ranking process was to characterize the probability of occurrence of each failure mechanism. At this stage of the analysis, a relative probability scale was defined. Events with a recurrence interval of 0-20 years (and probability of occurrence of .05-1.0) were assigned a

TABLE A-4.

FREQUENCIES OF INITIATING EVENTS AND FAILURE PROBABILITIES FOR LAND DISPOSAL COMPONENTS

Initiating Event/Component	Frequency of Occurrence	Annual Probability	Expected Life Time	Source
Natural Events				
100-year floods		.01		Leopold, et al
Freeze-thaw episodes	1-200/yr			Leopold, Baker
Sinkhole collapse	once per year in "county-sized" area (100's of square miles)			very general estimate based on a personal communication with Alexander
Wind erosion	several times/year			
Cracking due to moisture changes or thermal expansion	several times/year			USDA
Seismic event		.008 Los Angeles and San Francisco area .02 Imperial Valley		California Institute of Technology personal communication, Baker
Excess run-on		.04		Leopold, et al
Changes in ground-water table	once every 3-50 years			Interpreted from data by Dunne and Leopold
Slumping		.1-.01 per 260 Km^2		Baker

TABLE A-4.

FREQUENCIES OF INITIATING EVENTS AND FAILURE PROBABILITIES FOR LAND DISPOSAL COMPONENTS (Continued)

Initiating Event/Component	Frequency of Occurrence	Annual Probability	Expected Life Time	Source
Component Failure due to Improper Installation, Construction or Maintenance				
Leaks in Liner due to improper seals		.01		Interpretation of data from Southwest Research Institute
Pinhole leaks due to improper seals mechanically caused cuts and punctures	6.4-8.4/100m ofseam .9-3.0/1000m^2 of 60 mil HDPE			Interpretation of data from Kastman
Cracks in cover due to subsidence	1-2 years (after installation) 1-30 years after installation (low potential for subsidence after end of post-closure period)			Griffin et al Discussion with SCS
Cracks in cover due to excessive drying	2-10 years			Interpretation of data by Prudic
General human error of commission		$3x10^{-3}$		Wash-1400
Design errors		$3x10^{-2}$		Wash-1400
Inspection error (inspector fails to recognize initial error by operator)		.1		Wash-1400
Overflow of fill area because of bath-tub effect	5-10 years			Interpretation of data from Prudic, et al and Matuszek, et al, Kelleher

TABLE A-4.

FREQUENCIES OF INITIATING EVENTS AND FAILURE PROBABILITIES FOR LAND DISPOSAL COMPONENTS (CONTINUED)

Initiating Event/Component	Frequency of Occurrence	Annual Probability	Expected Life Time	Source
Leakage or rupture of flange or closure	$3x10^{-7}$/hr			
Leakage or rupture of valve	$1x10^{-8}$/hr			
Plugging of manual valve	$3x10^{-5}$/hr			
Plugging of motor operated valve	$3x10^{-5}$/use			Wash-1400
Failure to operate - motor operated valve	$1x10^{-3}$/use			Wash-1400
Swelling of synethetic liner and loss of resistence	1.5-4 years after installation depends on membrane type			Interpretation of data by Haxo
Acts of vandalism	$3x10^{-7}$/hr			Interpretation of data by SCS
Dissolution of clay liner by incompatible waste			hours to days	Green, et al
Plugging of leachate collection systems			9 years	Bass
Aging of leachate collection tiles			50 years	
Cracking of Cover Liners				
Concrete			40 + years	Pertusa
Soil Cement			25 + years	Pertusa

TABLE A-5. CLASSIFICATION OF LANDFILL COMPONENT FAILURES

LEGEND

NO SYMBOL - Not applicable; or low severity; or moderate severity and low probability

△ - Moderage severity and moderate to high probability

▲ - High severity

		DESIGN COMPONENT																	
	FAILURE MECHANISMS	Berm	Top Soil	Vegetation	Soil Poisoning	Drainage Layer	Drainage Tile	Synthetic Cover Liner	Composite Cover Liner	Fill to Grade	Active Fill Area	Buffer	Leachate Collection	Sump and Pump	Upper Liner (Syn.)	Leachate Detection	Lower Liner (Syn.)	Subgrade	Groundwater Monitoring
Natural Events	Excess Run-Off (erosion)	▲	△	△															
	Slumping	△																	
	Vegetative Growth							△	△										
	Death of Vegetation (loss of cover)		△	△							▲								
	Animal Burrowing		△					△	△						▲		▲		
	Moisture/Thermal Expansion		△																
	Rise of Groundwater Table										▲				▲	▲	▲	▲	
	Microbial Attack							△							△		△		
Location Specific Event	Freeze/Thaw		△												▲				
	Wind (erosion)																		
	Permafrost Melt		△					△	△										
	Flooding	▲	△			△	△	△	△		▲		△						
	Seismic Activity (faulting)										▲		△		▲	▲	▲		
	Sink Hole Collapse										▲		△		▲	▲	▲		
Operation and Maintenance	Material Aging/Life Expectancy				△		△	△	△				▲	▲	▲	▲	▲		
	Consolidation/Subsidence						△	△	△	△	▲	△	▲	▲	▲	▲	▲		
	Hard Pan Formation										△		▲						
	Ponding or Excess Hydrostatic Forces		△			△	△	△	△		△				△		△		
	Swelling Due to Moisture							△	△						▲		▲		
	Incompatible Wastes Interaction										▲			△	▲		▲		
	Drum Failure							△	△		▲								
	Breach of Security/Vandalism		△	△							▲								△
	Silting or Clogging						△						▲	▲		▲			▲
	Incompatible Waste/Component Interaction												▲	▲	▲		▲		
Poor/Improper Construction	Damage During Construction							△	△						▲	▲	▲		
	Insufficient Compaction							△	△	▲		△							
	Improper Sizing	▲	△			△	△	△	△				▲	▲				▲	
	Insufficient Thickness	▲	△				△	△	△	△		△			▲	▲	▲	▲	
	Improper Sealing							▲	△				▲	▲	▲		▲		
	Improper Grading and Subbase Preparation						△	△	△	▲			▲		▲		▲	▲	
	Non-Optimum Moisture Content of Material																		
	Exposure to UV Light							△							△		△		
Poor/Improper Design	Absence of Gas Migration Trench or Vent							△	△		▲		△						
	Undersizing	△						△	△				▲						
	Poor Material Selection (structural weakness)		△				△	△	△						▲		▲		
	Inadequate Groundwater Monitoring																		▲
	Inadequate Thickness							△	△				▲		▲		▲	▲	
	Inadequate Slope												△						

TABLE A-6. CLASSIFICATION OF SURFACE IMPOUNDMENT COMPONENT FAILURES

LEGEND

NO SYMBOL - Not applicable; or low severity; or moderate severity and low probability

△ - Moderate severity and moderate to high probability

▲ - High severity

		DESIGN COMPONENTS															
	FAILURE MECHANISMS	Berm	Topsoil	Vegetation	Soil Poisoning	Drainage Layer	Drainage Tile	Clay Cover Liner	Synthetic Cover Liner	Composite Cover Liner	Fill to Grade	Active Impoundment	Buffer	Upper Liner (Syn. or Clay)	Leachate Detection	Lower Liner (Syn. or Clay)	Groundwater Monitoring
Natural Event	Excess Run-Off (erosion)	▲	△	△													
	Slumping	△															
	Vegetative Growth							△	△	△							
	Death of Vegetation (loss of cover)		△	△													
	Animal Burrowing								△	△				▲		▲	
	Moisture/Thermal Expansion																
	Rise of Groundwater Table											△		▲	▲	▲	
	Microbial Attack								△					△		△	
	Wind (wave action)	△												△			
Location Specific Event	Freeze Thaw													▲			
	Wind (erosion)		△	△													
	Permafrost Melt					△	△										
	Flooding	▲	▲	▲								▲					
	Seismic Activity (faulting)											▲		▲	▲	▲	
	Sinkhole Collapse											▲		▲	▲	▲	
Operation and Maintenance	Material Aging/Life Expectancy				△		△		▲	△				▲	△	▲	
	Consolidation/Subsidence					▲	▲	△	▲	△	△		△	△		△	
	Ponding or Excess Hydrostatic Forces		△														
	Swelling Due to Moisture							△									
	Incompatible Waste Interaction													▲	△	▲	
	Breach of Security/Vandalism	△	△	△								△		△			△
	Silting or Clogging																▲
	Incompatible Waste/Component Interaction													▲		▲	
	Volatilization																
Poor/Improper Construction	Damage During Construction								△	△				▲*	▲	▲*	
	Insufficient Compaction							△	△	△	▲		△	△		△	
	Improper Sizing	▲	△			△	△	△	△	△				▲	△	▲	
	Insufficient Thickness	▲	△					△	△	△	△		△	▲		▲	
	Improper Sealing								▲	△				▲		▲	
	Improper Grading and Subbase Preparation							△	△	△	▲			▲	△	▲	
	Non-Optimum Moisture Content of Material													▲		▲	
	Exposure to UV Light								△*					▲			
Poor/Improper Design	Absence of Gas Migration Trench or Vent								△	△							
	Undersizing	△							△	△				▲		▲	
	Poor Material Selection (structural weakness)		△					△	△	△				▲		▲	
	Inadequate Groundwater Monitoring																▲
	Inadequate Thickness						△	△			△		△	▲		▲	
	Inadequate Slope																
	Absence of Inlet and Outflow Structures	△												△			

* High severity only if synthetic liner, if clay liner it would have no symbol

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high relative probability, those with a recurrence interval of 20-100 years (0.01-0.05) moderate relative probability, and those with a recurrence interval larger than 100 years (<.01) a very low relative probability. Where possible, the failure case studies and other published data, were used to assign the relative probability classes to the failure mechanisms. Otherwise, discussions during the peer review process and engineering judgment were used to estimate the relative frequency of occurrence of the failure mechanisms.

The failure event-component combinations were also evaluated with respect to severity. Evaluation factors used to rank severity are shown in Table A-7. For example, the volume of release dictates the cost of remedial actions and so the larger a release directly attributed to a component failure, the higher the severity. A component failure may not result in immediate release but might overload and in turn cause failure of other components; an example would be the development of cracks in a cover resulting in increased infiltration and overloading of the leachate collection system. The larger the relative volume of leachate that passes through a functioning component, the larger its impact on downstream components if it fails. Each of the major components was assigned a proportion of incipient liquid for pre-closure and post-closure periods, as indicated in the first two columns of Table A-5. Components which handle relatively high leachate volumes, were assigned high severity ratings in terms of spin-off to other components. Consequently, cover systems, which theoretically should process more liquid than other components, are more critical to the performance of the system than other components.

Replacement cost was another factor used in evaluating the severity of component failures. In general, components at the bottom of a facility entail greater excavation costs to replace them. Consequently, replacement costs are higher for these components, and a high severity index has been assigned to these components. Similarly, failure in components near the bottom of a facility are more difficult to detect since they are not

TABLE A-7.

COMPONENT FAILURE EVALUATION FACTORS

Component	[†]Leachate Volume (%)		Spinoff to Other Components		Replacement Cost	Ease of Detection
	Pre-Closure	Post-Closure	Pre-Closure	Post-Closure		
Berm	-	varies	-	L-H	L	H
Cover	-	100	-	H	L	H
Drainage Collection System	-	90-99	-	H	M	H
Cover Liner (clay)	-	10	-	M	M	M
Cover Liner (synthetic)	-	1	-	M	M	M
Active Fill Zone	100	1-10	H	M	H	M
Leachate Collection System	99	1-10	H	M		
Upper Containment Liner	1	.01-1	L	L	H	L-M
Leachate Detection System [*]	1	.01-1	M	L	H	L
Lower Containment Liner (synthetic)	1	.01-1	M	L	H	L
Groundwater Monitoring Wells	1	.01-1	L	L	L	M-H

[†] Relative volume of leachate which passes through each component assuming proper functioning of all units. Leachate volume is relative to incipient precipitation of 100 units.

[*] Passive Leachate Detection System

directly observable. An undetected component failure might result in the continuing release of leachate and the generation of an ever-growing plume of contamination. As a result, components that are difficult to monitor have been assigned a high severity index.

Each of the failure event-component combinations were evaluated with respect to the four severity indices (to yield an average severity index) and relative frequency of occurrence. Events with a moderate to high severity index in combination with a short recurrence interval (high frequency events) were assumed to be the most critical with respect to system performance (solid triangles in Table A-7); those with a moderate severity index and a moderate to high level of frequency were assumed to be less critical (open triangle); those with a low severity index, or the combination of moderate severity with low frequency level (or non-applicable combinations) were assumed to be the least critical in terms of system performance (no symbol). The selection of failure scenarios was based upon the linking of the most critical event conditions in Table A-5 and A-6.

3.3 Fault-Tree Analysis

Fault-tree analysis is an approach that can be used to examine alternative design and operating standards that may reduce the probability of technological system failure; failure is defined in this study as an uncontrolled release of toxic materials to the environment. A risk assessment study for a particular system should determine the relationship between the probability of a release event and the severity of its resulting impact, in other words, attendant losses. Losses can include death or injury to personnel, damage to capital equipment, cessation of service, air and water pollution, adverse public health effects, and costs for ameliorative actions. Two major objectives of fault-tree analysis are: (1) to identify the causal relationships between system components, environmental stresses, and human errors which may result in system failure; and (2) to minimize such failure through modifications in design, site location, or operation and maintenance procedures.

Fault-tree analysis was developed at the Bell Laboratories during the early 1960's to evaluate failure sequences and to estimate failure probabilities in missile launch systems. Its use has been widespread since its inception, particularly in application to nuclear reactor and chemical plant design. Some advantages of fault-tree analysis are that it is easily understood, widely used and accepted, and very useful for elucidating failure relationships.

In fault-tree analysis, a top or ultimate failure event is first selected. This would be analogous to a release of toxic material or a component failure event requiring some mitigating action, such as a cleanup operation or replacement of equipment. This system failure event (top event) is traced backwards to identify all relevant intermediate failure events which might lead to it. These events are in turn traced back to determine their antecedant failure events. In this manner, a branching network of inter-connected events is constructed: the fault-tree. The analysis is continued until no further reduction is possible or no data are available.

The tree is then "pruned" by eliminating very high or very low probability events and by eliminating non-pertinent events. After the tree has been reduced to its desired level of detail, the probability of each of the basic failure events is determined. The probability of the ultimate failure is a combination of the conditional probabilities of the intermediate failure events.

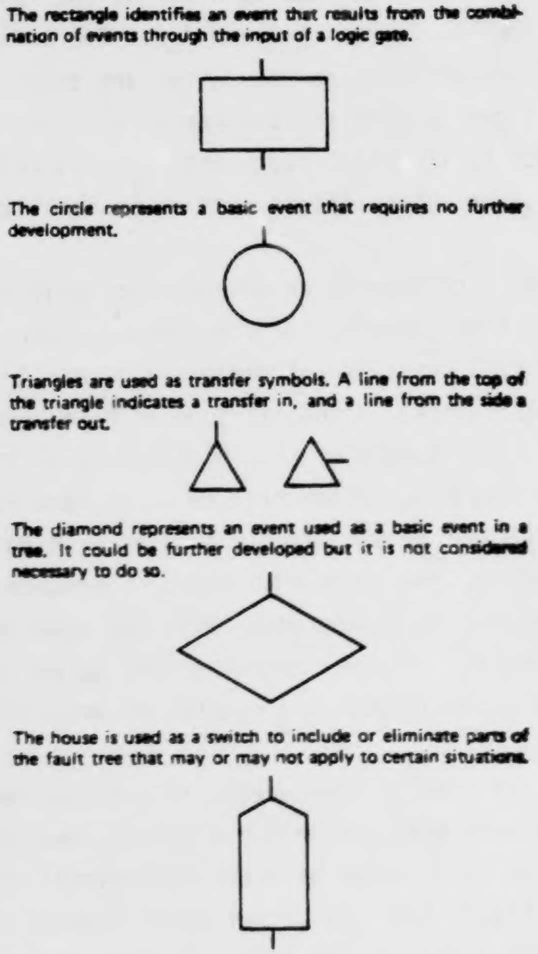
The failure mechanisms determined to be the most critical were combined to form a series of failure scenarios. These represent combinations of events and component failures that either result in the generation of leachate or a release of leachate through the containment system. Examples of the first type of event include infiltration of precipitation through the cover, fluctuations of the groundwater table above the base of the facility, and innundation by flood waters. The volumes of liquid in these hydrologic inputs were determined by engineering analysis and are strongly dependent on facility area.

Fault-trees are comprised of a standardized set of schematic symbols which represent the linkages of initial and subsidiary events to a top event. The symbols which will be used to describe the failure scenarios in this report are shown in Figures A-7 and A-8. Two or more events are connected by various types of logic gates. A failure event results from the occurrence of two or more failure events through a gate. A basic failure, as represented by a circle, represents an initiating event at the bottom of a fault-tree, for which failure rate or probability data is available.

A diamond symbol represents an undeveloped event that is included in an initial fault-tree analysis for completeness only. Quantitative evaluation of an undeveloped event is not performed generally because of time or financial constraints. A special type of basic event is a house gate which can be selectively turned on or off depending on the interest of the analyst. For example, system failure which results from locational characteristics can be effectively handled with house gates. When a house gate is turned on, the associated event is presumed to occur. Transfer triangles are used to conveniently link the same input event to two or more succeeding events. The oval symbol refers to an input event which is involved in a probabilistic logic gate, as described in the next section.

Gate symbols are used to link events in a fault-tree. One of more events may be inputs to a gate but only one output event can result from a gate. There are three basic types of gates and several variations of them, as indicated in Figure A-8. An output event from an .AND. gate occurs if all the input events occur at one time. An output event from an .OR. gate occurs when any of the input events take place. The inhibit gate is the third type of gate and differs from the preceding examples of deterministic gates. It is probabilistic in nature because the output from an inhibit gate is not totally determined from the input events. The inhibit gate requires an input event and a conditional event (which is represented by an oval symbol). An example of an inhibit gate would be a conditional failure in response to an initiating event. An example would be the conditional rupture of a storage tank (say 50 percent) subjected to an earthquake event.

FIGURE A-7. FAULT TREE EVENT SYMBOLS



The rectangle identifies an event that results from the combination of events through the input of a logic gate.

The circle represents a basic event that requires no further development.

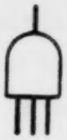
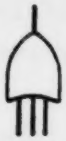
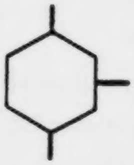
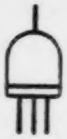
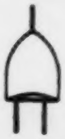
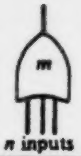
Triangles are used as transfer symbols. A line from the top of the triangle indicates a transfer in, and a line from the side a transfer out.

The diamond represents an event used as a basic event in a tree. It could be further developed but it is not considered necessary to do so.

The house is used as a switch to include or eliminate parts of the fault tree that may or may not apply to certain situations.

(Schreiber, 1982)

FIGURE A-8 FAULT TREE LOGIC GATES

	Gate Symbol	Gate Name	Causal Relation
1		AND gate	Output event occurs if all input events occur simultaneously.
2		OR gate	Output event occurs if any one of the input events occurs.
3		Inhibit gate	Input produces output when conditional event occurs.
4		Priority AND gate	Output event occurs if all input events occur in the order from left to right.
5		Exclusive OR gate	Output event occurs if one, but not both, of the input events occur.
6	 *n* inputs	*m* Out of *n* gate (voting or sample gate)	Output event occurs if *m* out of *n* input events occur.

(Henley and Kumamoto, 1981)

The probability of a top event in a fault-tree is determined from the probabilities of the intermediate events and evaluation of the logic gates connecting the events. Boolean algebra is used to represent the operations of the gates in the fault-tree. The result of an .AND. gate is the product of the probabilities of the input events, whereas the result of an .OR. gate is the Boolean sum of the probabilities of the input events. These combinations are illustrated in a fault-tree presented by Morgan (IEEE Spectrum, 1981) to describe the ways in which a rubber-band-powered airplane could fail if the propeller is wound more than the recommended number of turns (Figure A-9).

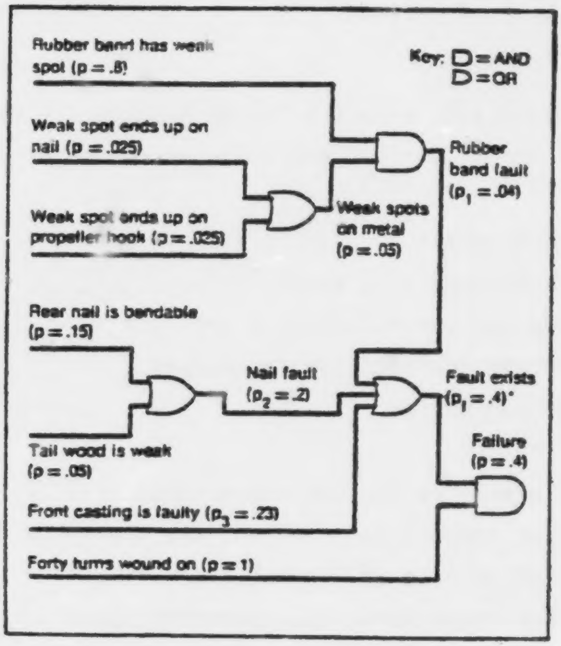
In the case of very small probabilities, the Boolean sum can be approximated by the algebraic sum of the probabilities. In some cases, the probabilities of the input events are constant or time invariant. Often the probability of a component failure (particularly for a system which is subject to varying environmental conditions) is not constant, however. The probability of failure may increase with time due to material aging, for example.

3.3.1 Failure Scenarios

The most critical failure events identified in the component failure chart of Tables A-5 and A-6 were combined to form failure scenarios. Scenarios are groups of events which represent realistic pathways to system failure. The events consist of three basic types: (1) the occurrence of natural initiating events, (2) the function (or dysfunction) of components in response to these initiating events or to aging processes and (3) operation and maintenance activities that may or may not detect and repair failed components.

As described previously, the fault-trees describing each of the failure scenarios, are constructed of a series of basic events, intermediate events and a top event. The top event in each of the scenarios is either the generation (or addition) of liquid to the disposal area or release of

FIGURE A-9 EXAMPLE FAULT TREE WITH PROBABILITY CALCULATIONS


Rubber band has weak spot ($p = .8$)
Key: D = AND
D = OR
Weak spot ends up on nail ($p = .025$)
Rubber band fault ($p_1 = .04$)
Weak spot ends up on propeller hook ($p = .025$)
Weak spots on metal ($p = .05$)
Rear nail is bendable ($p = .15$)
Nail fault ($p_2 = .2$)
Fault exists ($p_1 = .4$)*
Tail wood is weak ($p = .05$)
Failure ($p = .4$)
Front casting is faulty ($p_3 = .23$)
Forty turns wound on ($p = 1$)

*Since all three faults can occur together,

$$p_t = 1-(1-p_1)(1-p_2)(1-p_3) = .4$$

A. Fault tree with associated probabilities(p) for failure of a rubber-band airplane if 40 turns are wound onto the rubber band.

(Morgan, 1981)

leachate from the containment system. Fault-tree analysis was selected as an appropriate technique since its flexibility permits the incorporation of a variety of factors that could result in failure and since both time-dependent and time-independent events can be evaluated within a single framework.

The failure mechanisms selected for this study are summarized in Table A-8. The scenarios are classified according to the major type of failure:

- Natural event
- Location-specific event
- Operation and maintenance problems
- Improper construction techniques
- Improper design

The other table entries include the technologies for which the scenarios apply, the major components affected, the timing of the failure event, the relative rate of release of leachate resulting from the failure, spin-off effects to other components, and operating specifications which could be employed to reduce the occurrence of failure. Three scenarios (Wind Erosion, Improper Operation and Maintenance, and Acid Leaching) were not included in the final analysis since they applied to waste piles and land treatment facilities. These technologies were omitted from the Liner-Location Study. A fourth scenario (Inadequate Groundwater Monitoring) was also dropped from the analysis at the request of the project monitor. It is anticipated that this type of scenario will be included in a future version of the model in order to incorporate corrective actions in the model framework.

The fault-trees describing the failure scenarios are shown in Figures A-10 through A-23. Each labeled event is identified by an alphanumeric label which is defined in Table A-9. The events in the fault-trees represent one or more of the following types of elements:

TABLE A-8. SELECTED FAILURE SCENARIOS AND FACILITY COST MODEL LINKAGES

Failure Mechanism	Failure Type					Technology				Component	Timing	Rate	Performance Linkage	Design Alternatives
	NE	L	O/M	C	D	LF	S	W	LT					
Material Aging			X			X	X	X		Containment liner	Post-closure	Slow	Reduction of LCS efficiency, increased liner permeability	Thicker liner, liner inspections, excavation and replacement
Consolidation			X			X	X	X		Cover liner	Post-closure	Slow	Increased liquid inactive area, increased cover permeability	Cover inspections, crack repair, pre-compaction, thicker liner
Drum Failure			X			X				Cover liner Containment liner	Post-closure	Slow	Increased liquid in active area, reduction of DCS efficiency, increased cover permeability	Internal berms crack repair, thicker liner
Incompatible Waste/ Component Interaction			X			X	X	X		Containment liner	Pre/post-closure	Sudden	Reduction of LCS efficiency, increased liner permeability	Waste compatibility testing
Damage During Construction				X		X	X	X		Containment liner	Pre/post-closure	Slow	Reduction of LCS efficiency, increased liner permeability	Installation inspection, buffer layer
Improper Sealing				X		X	X	X		Containment liner	Pre/post-closure	Slow	Reduction of LCS efficiency, increased liner permeability	Inspection of seals, better sealing technique
Inadequate thickness					X		X			Containment liner	Pre-closure	Slow	Increased leakage through liner	Thicker liner
Erosion due to excess run-on	X					X				Berm	Pre-closure	Sudden	Release of waste constituents, increased infiltration	Stronger berms, temporary pumps and treatment
Animal Burrowing	X						X			Containment liner	Pre-closure	Sudden	Increased permeability of liner	Poison layer
Rise of G.W. Table	X		X			X	X	X		Containment liner	Pre/post-closure	Slow	Increased liquid in active area	G.W. Monitoring, dewatering, thicker liner
Silting or Clogging			X			X		X		Leachate collection	Pre/post-closure	Slow	Increased tile spacing in LCS	Buffer zone
Inadequate G.W. Monitoring					X	X	X	X	X	Subgrade	Post-closure	Slow	Undetected growth of plume	More monitoring wells, detailed hydrogeologic study
Flooding		X				X	X			Berm	Pre/post-closure	Sudden	Increased infiltration, release of waste constituents	Stronger berms, temporary pumps and treatment
		X				X	X	X		Active area	Pre-closure	Sudden	Release of waste constituents	Stronger berms, temporary pumps and treatment
		X						X		Indoor pile structure	Pre-closure	Sudden	Release of waste constituents	Stronger walls, temporary pumps and treatment
Wind Erosion		X						X		Active area	Pre-closure	Sudden	Dispersal of waste constituents	Dust control, indoor facility components

TABLE A-8 SELECTED FAILURE SCENARIOS AND FACILTIY COST MODEL LINKAGES (Continued)

Failire Mechanism	Failure Type					Technology				Component	Timing	Rate	Performance Linkage	Design Alternatives
	NE	L	O/M	C	D	LT	S	W	LT					
Inlet/Outlet Control Malfunction			X				X			Active Area	Pre-Closure	Sudden	Breach of Berm	Inspection frequency, dredging frequency, inlet/outlet pipe sizes
Improper Operation and Maintenance			X						X	Treatment Zone	Pre-Closure	Slow	Non-degradation of waste constituents	Run-on control, inspection and testing schedules
Catastrophic Releases		X				X	X	X	X	Active Area	Pre/Post-Closure	Sudden	Release of waste constituents, breach of liner	Siting requirements
Damage During Inspection			X					X		Containment Liner	Pre-Closure	Slow	Breach of Liner	Liner thickness, inspection schedule
Acid Leaching					X				X	Treatment Zone	Pre-Closure	Slow	Mobilization of waste constituents	PL Buffer, run-on control, drainage system design

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NE = Natural Event L = Location Specific Event O/M = Operation and Maintenance
C = Poor/Improper Construction D = Poor/Improper Design
LF = Landfill S = Surface Impoundment W = Waste Pile
LT = Land Treatment LCS = Leachate Collection System
DCS = Drainage Collection System

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS

LABEL	TECHNOLOGY LF	SI	WP	LT	NL	DISTRIBUTION TYPE*	DISTRIBUTION PARAMETER	DESCRIPTION
ABSEN	o				o	B	0.001	Buffer layer too thin or small diameter tile
ACIDA				o		B	0.37	Acid deposition area
BARRL	o				o	B	0.2	Placement of barrels (in landfill)
BATHB	o	o			o	P		Back-up of leachate into active fill area and leakage through cover causing bathtub effect
BDISS	o	o	o			C		Dissolution of bottom liner due to incompatible waste
BERBF	o	o	o		o	C		Flow of floodwater through berm into active area
BERBR	o	o	o		o	C		Flow of run-on through berm into active area
BERMB	o	o	o		o	B	0.001	Berm breached by erosion during a flood event (berm height = 0.67m)
BUFFR	o					T	50 years	Clogging of tiles in leachate collection system due to silting or chemical encrustation
BURRO	o	o	o		o	C		Presence of animals in facility area
BYPAS		o				B	0.375	Emergency storage of surface impoundment waste in a second impoundment
CATRL		o				C		Catastrophic release from a surface impoundment
CLAYL	o	o	o			B	0 or 1.00	Clay liner
CLOGG	o		o			C		Clogging of leachate collection system and reduction efficiency
CLOGT		o				B	0.0025	Outlet structure clogged (pipe diameter = 10")

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* B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent, LT = Lagged Triangular

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)

LABEL	TECHNOLOGY LF	SI	WP	LT	NL	DISTRIBUTION TYPE*	DISTRIBUTION PARAMETER	DESCRIPTION
CONSL	o	o			o	C		Consolidation of cover
COVER	o	o			o	P		Cover saturates
CRACK	o	o			o	C		Cracks form in cover
CRCKB	o	o	o		o	C		Cracks form in berm
DAMAB	o	o				B	.01	Damage to bottom synthetic liner during liner emplacement
DAMAC	o	o			o	B	0.01	Damage to synthetic cover liner during emplacement
DAMAG	o	o	o			B	0.01	Damage to top synthetic containment liner during emplacement
DAMAL			o			T	37 years	Damage to liner during inspection
DCSOV	o	o				P		Drainage collection system efficiency reduced because of: 1) cover liner rupture; or 2) drainage collection system slope reduction due to subsidence
EARTH	o	o	o	o	o	T	100 years	Earthquake event
EROSN	o	o			o	LT	1.5-40 years	Loss of cover
EVENT	o	o	o		o	B	0.0004	Event occurs on same day as inspection (weekly inspection)
EVNOC	o	o	o		o	B	0.0023	Event occurs on a day with no inspection (weekly inspection)
EXCSS				o		C		Excess moisture in treatment zone
EXEVR		o				B	0.001	Excessive rainfall event

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* B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent

LT = Lagged Time Dependent

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)

LABEL	TECHNOLOGY					DISTRIBUTION* TYPE	DISTRIBUTION PARAMETER	DESCRIPTION
	LF	SI	WP	LT	NL			
EXPAN	o	o	o		o	B	.035	Expansive soils causing cracks in berm (berm hight = 0.67m)
FFILL	o		o		o	B	.001	Runon volume ≥ available active fill volume
FLOOD	o	o	o		o	B	0.07	Flood prone area
FLVOL	o		o		o	B	.001	Floodwater volume ≥ available active fill volume
FREEB	o	o	o		o	B	0.0 or 0.5	Insufficient depth to groundwater table
FREEL	o		o		o	B	0.05	Free liquids in waste
FREEZ	o	o	o		o	B	0.001	Freeze thaw cracking (berm thickness = 0.67m)
GWTAB	o	o	o		o	T	35 years	Rise of groundwater table
IMPMO				o		B	0.125	Improper moisture
IMPPH				o		B	0.03	Improper pH
IMPWA				o		B	0.001	Improper waste application rate
IMPWT				o		B	0.001	Improper waste type
INADM				o		B	0.89	Inadequate monitoring at land treatment facility (1 lysimeter)
INADR				o		B	0.001	Inadequate run-on control
INADS				o		B	2.1×10^{-11}	Inadequate slope (2% slope)
INADD		o				B	0.0 or 1.00	Clay liner thickness is inadequate to prevent seepage (thickness = 1m)
INADL			o			P	34% to 99%	Inadequate leachate collection in waste pile

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* B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent, LT = Lagged Triangular

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)

LABEL	TECHNOLOGY LF	SI	WP	LT	NL	DISTRIBUTION TYPE*	DISTRIBUTION PARAMETER	DESCRIPTION
INADZ	o	o	o		o	B	0.001	Inadequate sterilization of subgrade surrounding disposal facility
INCOM	o	o	o			C		Placement of incompatible waste
INDRG		o				T	339 years	Overflow due to inadequate dredging of surface impoundment
INFIL	o	o			o	C		Infiltration of precipitation through cover
ININB	o	o				B	0.1	Failure to repair bottom synthetic liner during inspection
ININC	o	o			o	B	0.1	Failure to repair cover synthetic liner during inspection
ININD		o				B	0.1	Failure to repair damaged liner during inspection
ININS	o	o	o			B	0.1	Failure to repair top synthetic liner during inspection
INSPL	o	o	o		o	B	0.001	Inspection error for repetitive event over the lifetime of the facility
INSRE	o	o	o		o	C		Non-inspection/non-repair of faulty component
INVER	o	o	o			B	0.005 (1.00 for incompatible waste scenario)	Inventory error (minimal inventory system)
IOERR	o	o	o		o	B	0.1	Inspection oversight
ISEAL	o	o	o		o	B	0.05	Improper seal of synthetic liner
KARFA	o	o	o	o	o	B	5.0×10^{-6}	Disposal facility lies within area affected by sinkhole collapse
KARST	o	o	o	o	o	B	0.095	Facility located in a karst area
LCSEF	o		o			P	25% - 99%	Reduction of leachate collection system efficiency in response to liner leakage

* B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent, LT = Lagged Triangular

TABLE A-9. **LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)**

LABEL	TECHNOLOGY					DISTRIBUTION TYPE*	DISTRIBUTION PARAMETER	DESCRIPTION
	LF	SI	WP	LT	NL			
LEAKT	o	o	o			C		Leakage through top containment liner
LDSAG	o	o				T	75 years	Aging of leachate detection systems due to corrosion
LDSAT	o	o				P	0. or 1.00	Saturation of leachate detection layer (leachate detection system thickness = 0.26m and input seepage is greater than 9.1cm)
LDSEL	o	o				B	0.005	Presence of electronic leachate detection system
LINER						C		
LINE1	o	o	o			T	35 - 36 years	Degradation of synthetic liner
LINE2,3	o	o				T	35 - 36 years	Aging of second containment liner
LIQUD	o		o	o	o	C		Presence of liquid in active area
LOWPH				o		B	0.5	Low pH precipitation event
NOBUF				o		B	0.75	Absence of pH buffer in land treatment unit
NOCOM	o	o	o			B	0.05 (1.00 for incompatible waste scenario)	No compatibility testing resulting in placement of incompatible wastes in facility
NOCON	o	o	o			B	0.001	No control of animal ingress
NOCOV			o			B	0.90	No cover
NONDG				o		C		Nondegradation of constituents in treatment zone
NOVEG	o	o			o	B	0.001	Absence of vegetative cover
OHUND	o	o	o		o	B	$1-(1-0.01)^n$	Occurrence of 100 year flood
PHYSL	o	o				B	.01	Synthetic liner puncture by physical loading (30 mil liner with 0.16m buffer)

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* B = Binomial, P = Performance Dependent, C = Conditonal, T = Time Dependent, LT = Lagged Triangular

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)

LABEL	TECHNOLOGY LF	SI	WP	LT	NL	DISTRIBUTION TYPE*	DISTRIBUTION PARAMETER	DESCRIPTION
PRCOC	o	o			o	T	1500 years	Insufficient pre-compaction
PRCOM	o				o	LT	3 years	Consolidation of cover in response to the formation of voids around barrels
PRECL/ POSTCL	o	o	o	o	o	Defined by length of simulation period		Event occurs during preclosure period/post closure period
PUMPC	o		o		o	P		Overloading of pump-out equipment
PUNCT	o	o	o		o	T	50 years	Insufficient puncture strenth of synthetic or clay liner
PUNC2/ PUNC3							50 years	Insufficient puncture strength in secondary liners
RAINF	o	o		o	o	B	0. or 1.00	Rainfall event in a given year
REDFR		o				C		Reduction in impoundment freeboard
RELEA	o	o	o	o	o	C		Release of leachate from containment system
REMOV			o			B	0.8	Periodic removal of waste (removal frequency = every 5 years)
RUNON	o	o	o		o	B	$1-(1-0.04)^n$	Excess run on (n = number of years in the simulation period)
RUPTR	o				o	T	25 years	Corrosion and rupture of buried barrels
SEIFA	o	o	o	o	o	B	0.00003	Disposal facility lies within an area affected by seismic event
SEISM	o	o	o	o	o	B	0.119	Facility located in seismically active area
SINKH	o	o	o	o	o	T	1 year	Sinkhole collapse

* B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent, L = Lagged Triangular

TABLE A-9. LIST OF FAILURE EVENTS, DISTRIBUTION TYPES, AND PROBABILITY PARAMETERS (continued)

LABEL	TECHNOLOGY LF	SI	WP	LT	NL	DISTRIBUTION TYPE	DISTRIBUTION PARAMETER	DESCRIPTION
SOLID	o	o	o		o	B	0.01	Consolidation of berm
SPILL	o	o				C		Flood or run-on water in facility
SYNTC	o	o			o	B	0 or 1.00	Presence of synthetic cover liner
SYNTH	o	o	o			B	0 or 1.00	Presence of synthetic liner
TDISS	o	o	o			T	0.06 years	Liner dissolution due to interaction with incompatible wastes
TEARB	o	o				C		Tear in bottom containment liner
TEARC	o	o			o	C		Tear in cover liner
TEARS	o	o	o			B/C	.001	Tear in top containmet liner
TENSL	o	o	o		o	B	Syn. = 0.0 Clay = 0.05	Groundwater table rise resulting in synthetic liner tear or rupture of clay liner
THINL	o	o	o		o	B	Syn. = 0.01 Clay = 0.001	Liner too thin in areas (off spec.)
TOPAC	o		o		o	LT	20 years	Degradation of synthetic cover liner
TOPAG	o	o				LT	20 years	Aging of clay cover liner
UNDER	o	o	o		o	C		Rise of groundwater to bottom of containment liner
UNDET	o	o	o		o	C		Undetected crack in berm
VEGPN	o	o	o		o	B	.001	Penetration into berm by vegetation (berm height = 0.61m)
WEAKS	o	o	o			C		Breach in liner

B = Binomial, P = Performance Dependent, C = Conditional, T = Time Dependent, LT = Lagged Triangular

FIGURE A-10

MATERIAL AGING

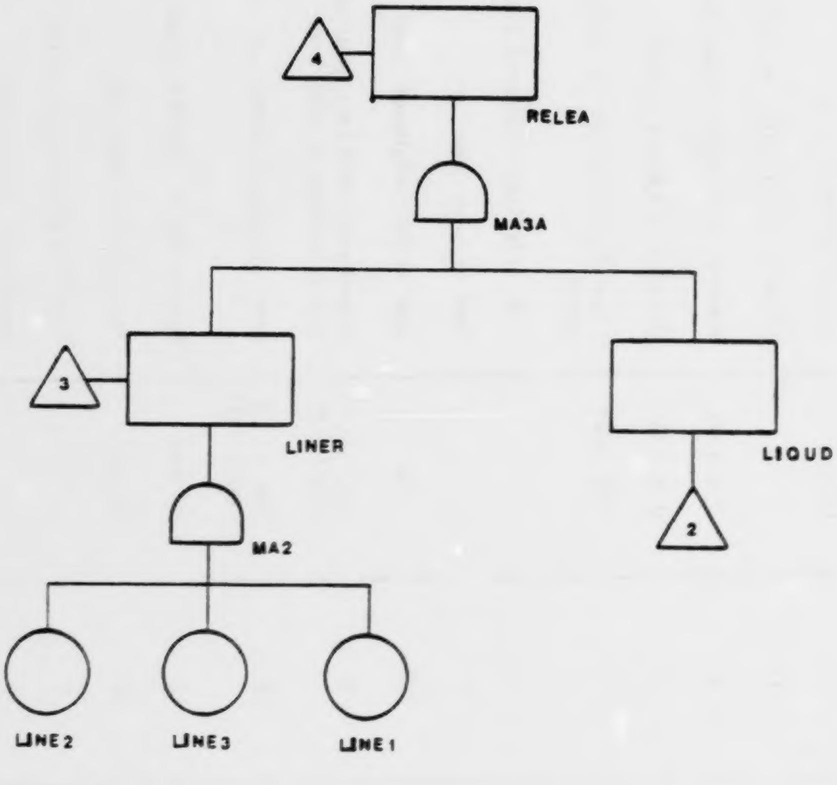

4
RELEA
MA3A
3
LINER
LIQUD
2
MA2
LINE2
LINE3
LINE1

FIGURE A-11
CONSOLIDATION

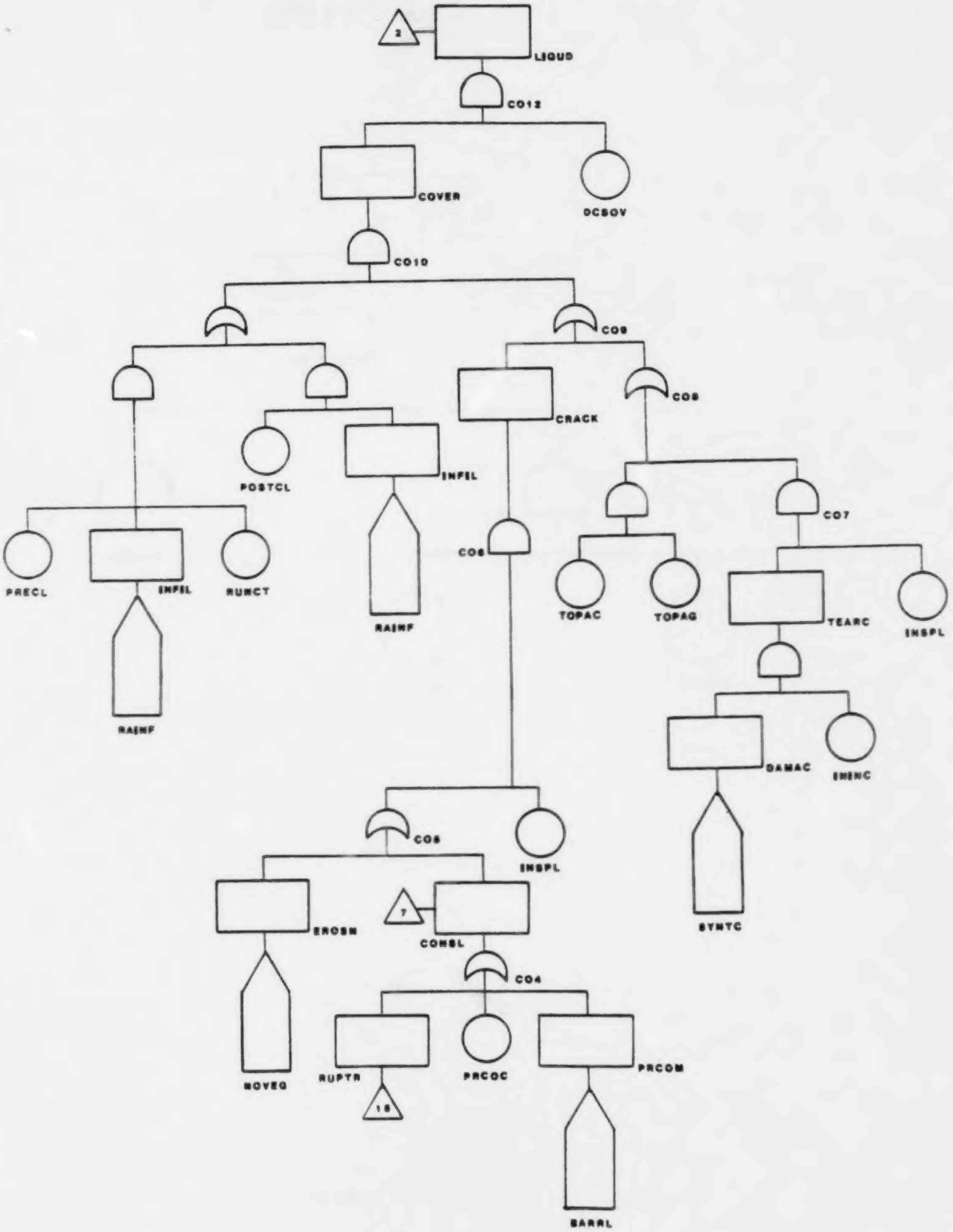

2
LIQUD
CO12
COVER
DCSOV
CO10
CO9
CRACK
CO8
POSTCL
INFIL
CO6
PRECL
INFIL
RUNCT
RAINF
RAINF
TOPAC
TOPAG
CO7
TEARC
INSPL
DAMAC
ININC
SYNTC
CO5
INSPL
EROSN
7
CONSL
CO4
NOVEG
RUPTR
15
PRCOC
PRCOM
BARRL

FIGURE A-12

DRUM FAILURE

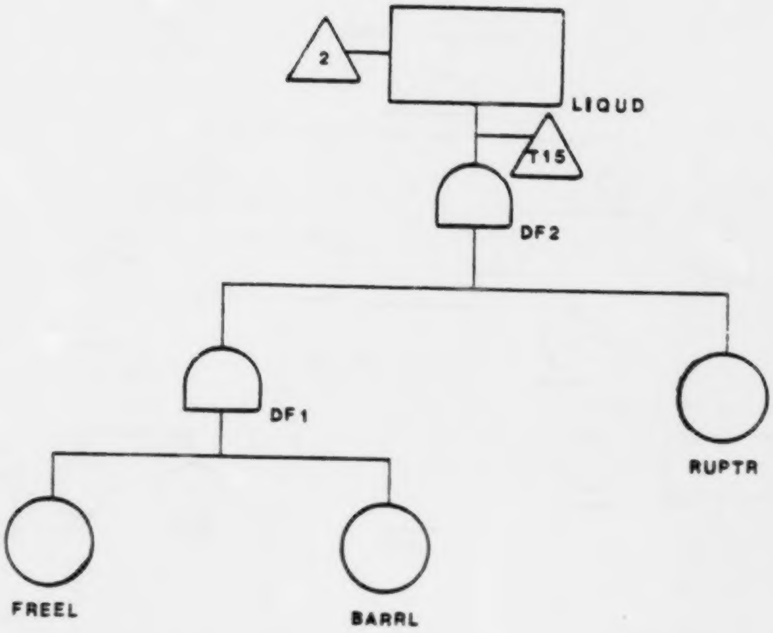

2
LIQUD
T15
DF2
DF1
RUPTR
FREEL
BARRL

FIGURE A-13

INCOMPATABLE WASTE

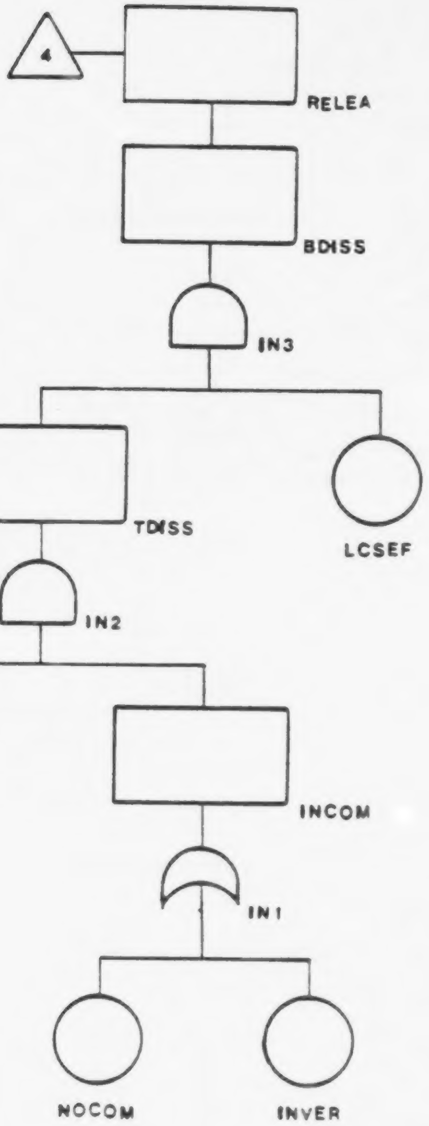

4
RELEA
BDISS
IN3
TDISS
LCSEF
IN2
FREEL
INCOM
IN1
NOCOM
INVER

FIGURE A-14
DAMAGE DURING CONSTRUCTION

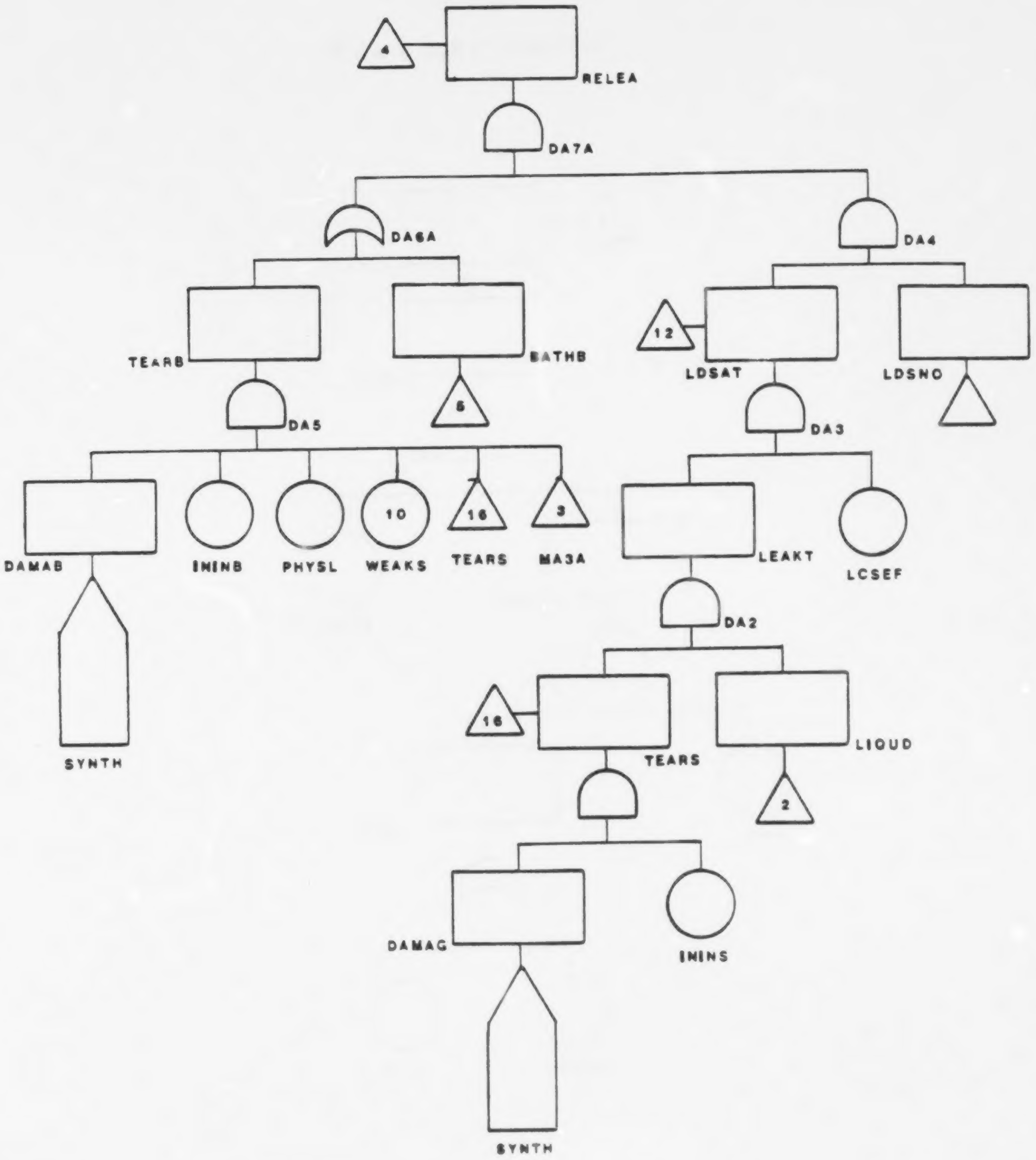

4
RELEA
DA7A
DA6A
DA4
TEARB
BATHB
12
LDSAT
LDSNO
DA5
5
DA3
10
16
3
DAMAB
ININB
PHYSL
WEAKS
TEARS
MA3A
LEAKT
LCSEF
DA2
16
TEARS
LIOUD
2
SYNTH
DAMAG
ININS
SYNTH

FIGURE A-15

IMPROPER SEALING

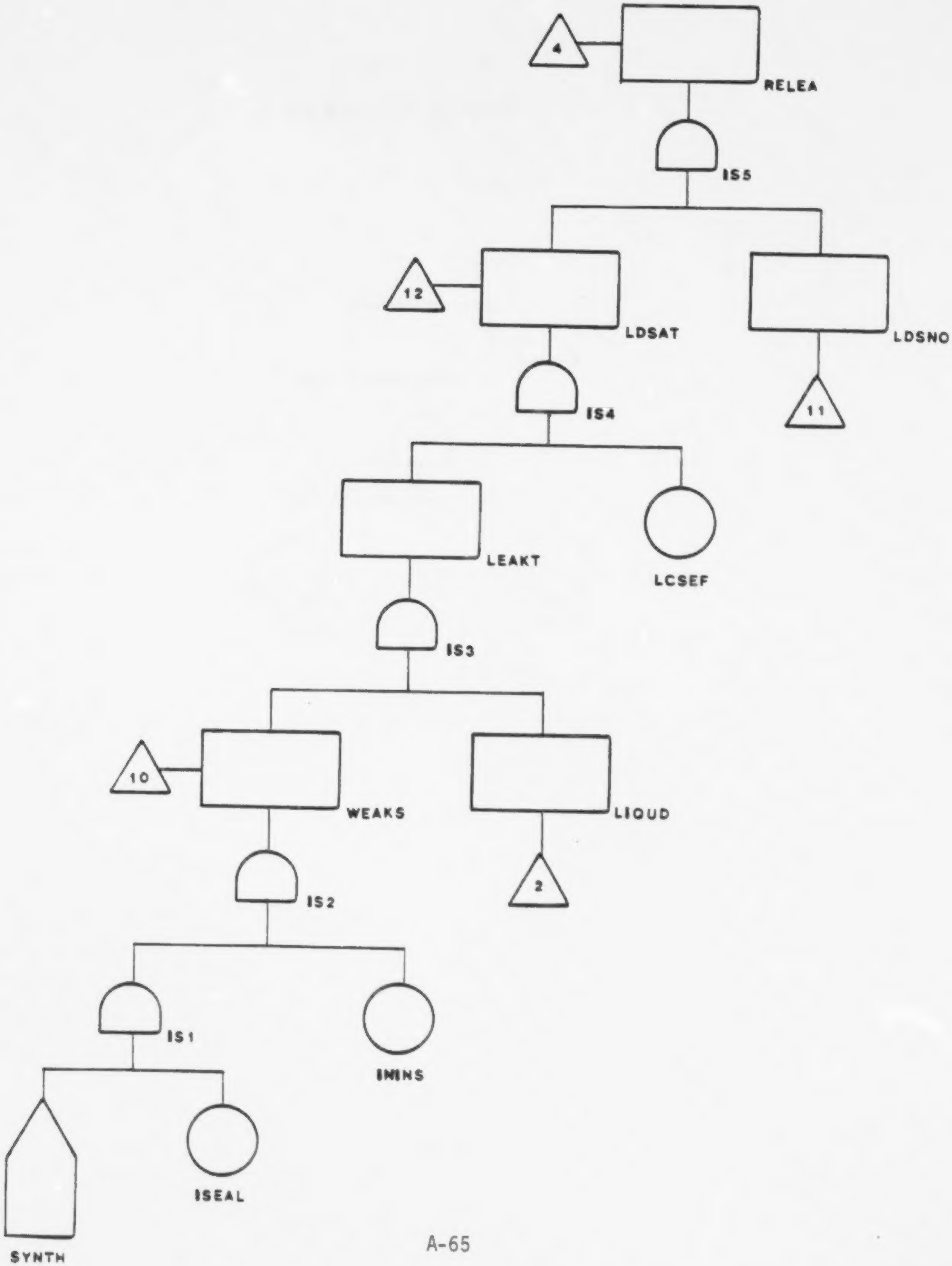

4
RELEA
IS5
12
LDSAT
LDSNO
11
IS4
LEAKT
LCSEF
IS3
10
WEAKS
LIQUD
2
IS2
IS1
IMINS
SYNTH
ISEAL

FIGURE A-16

INADEQUATE THICKNESS

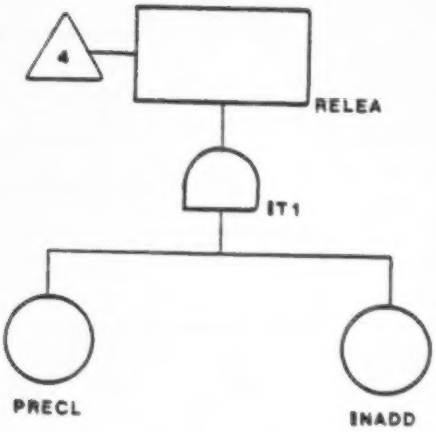

4
RELEA
IT1
PRECL
INADD

FIGURE A-17

EXCESS RUN-ON

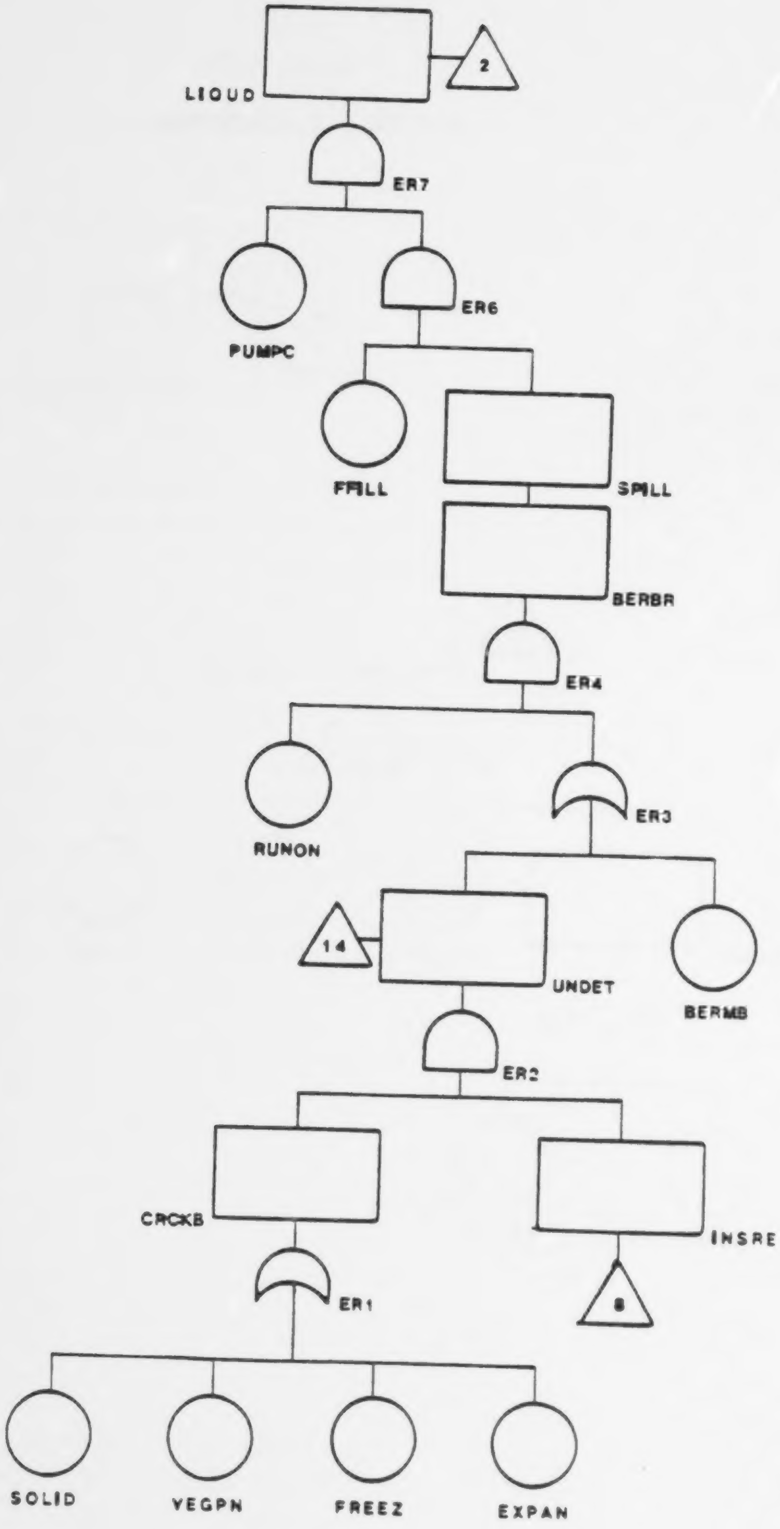

LIQUD
2
ER7
PUMPC
ER6
FFILL
SPILL
BERBR
ER4
RUNON
ER3
14
UNDET
BERMB
ER2
CRCKB
INSRE
ER1
8
SOLID
VEGPN
FREEZ
EXPAN

FIGURE A-18

ANIMAL BURROWING

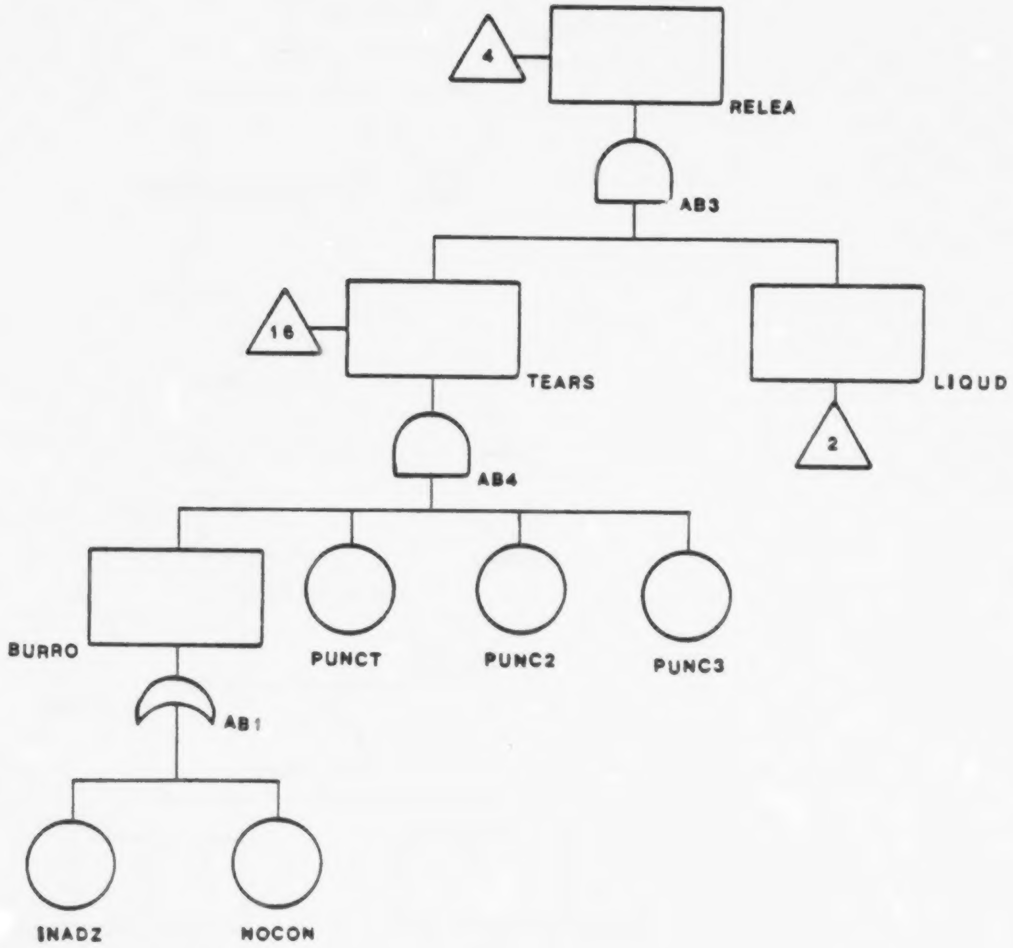

4
RELEA
AB3
16
TEARS
LIQUD
2
AB4
BURRO
PUNCT
PUNC2
PUNC3
AB1
INADZ
NOCON

FIGURE A-19

RISE OF GROUNDWATER TABLE

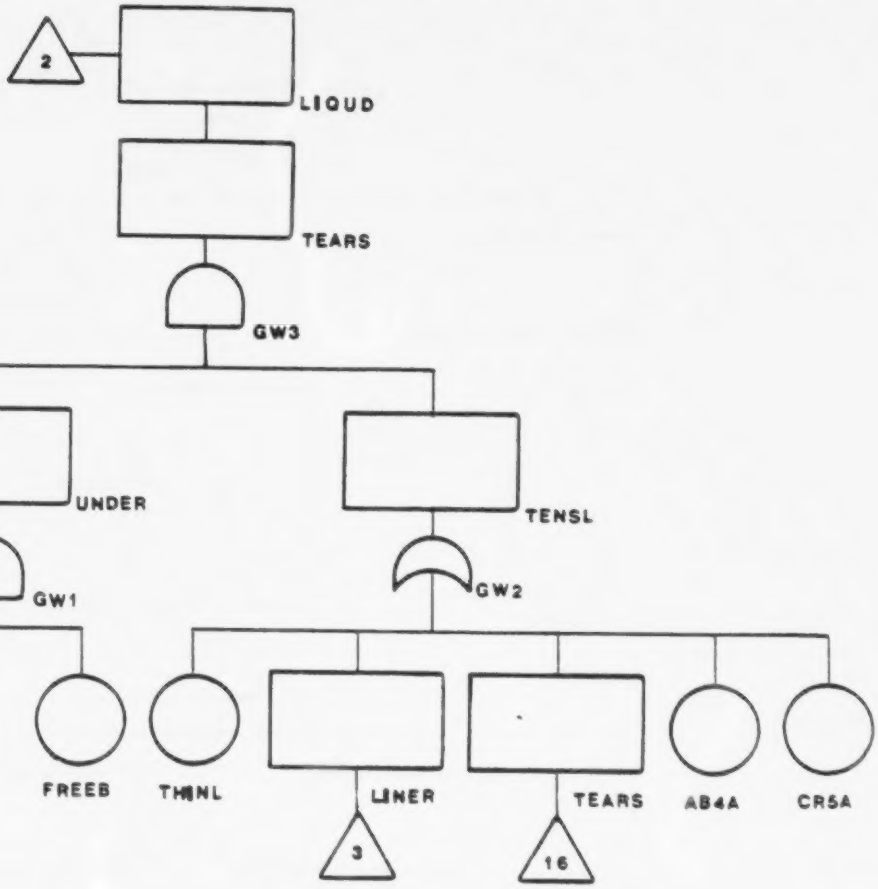

2
LIQUD
TEARS
GW3
UNDER
TENSL
GW1
GW2
GWTAB
FREEB
THINL
LINER
TEARS
AB4A
CR5A
3
16

FIGURE A-20
SILTING OR CLOGGING

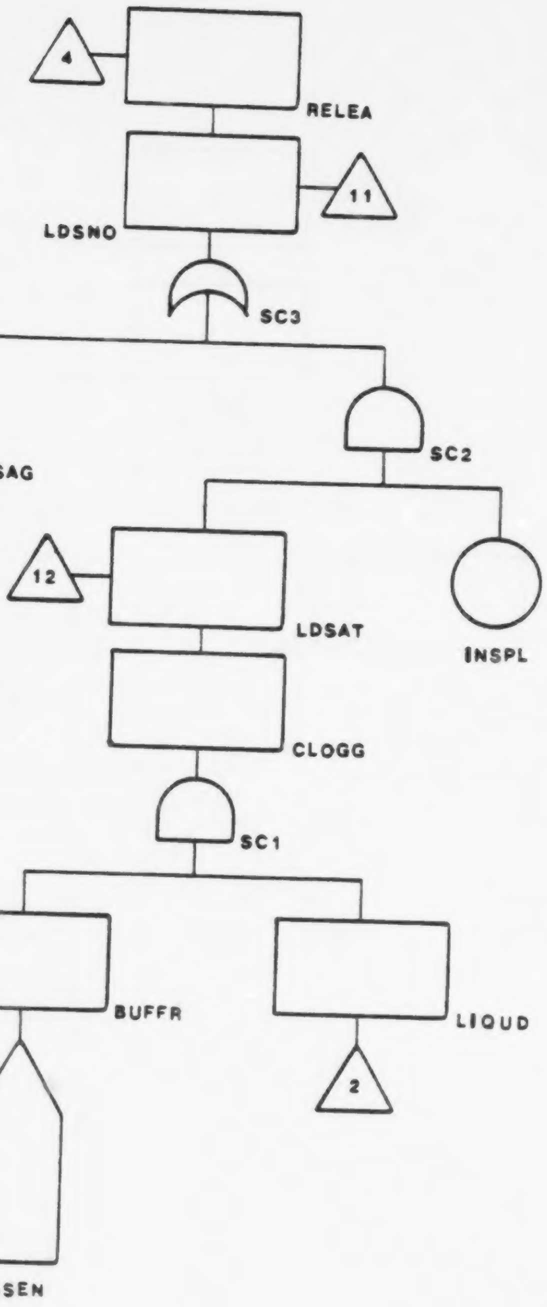
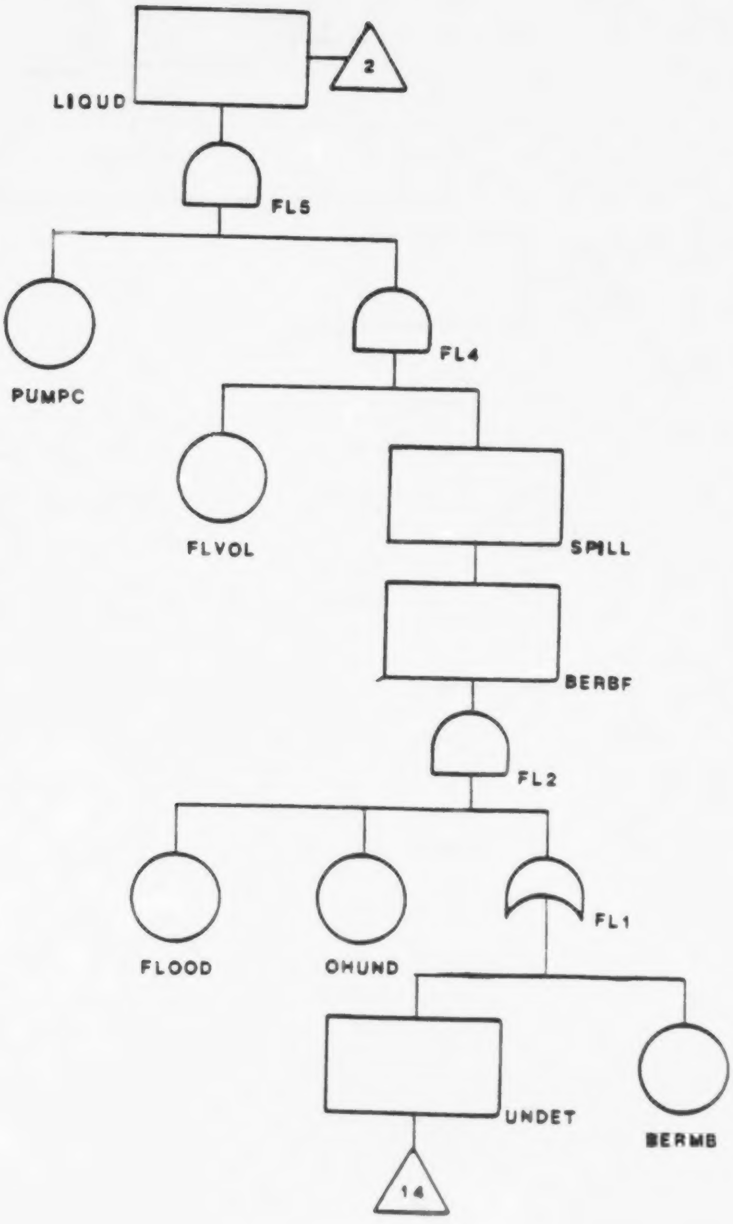

4
RELEA
LDSNO
11
SC3
LDSAG
SC2
12
LDSAT
INSPL
LDSEL
CLOGG
SC1
BUFFR
LIQUD
2
ABSEN

FIGURE A-21

FLOODING



2
LIQUD
FL5
PUMPC
FL4
FLVOL
SPILL
BERBF
FL2
FLOOD
OHUND
FL1
UNDET
BERMB
14

FIGURE A-22

INLET/OUTLET CONTROL MALFUNCTION

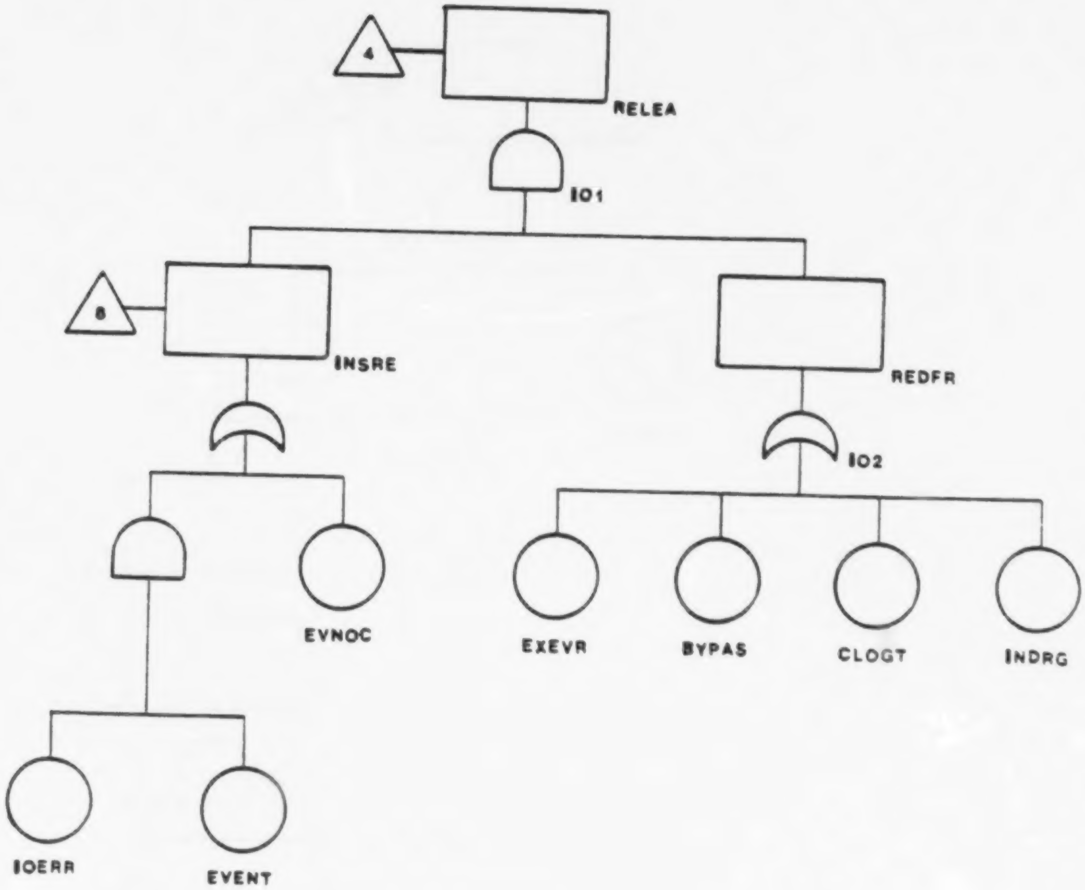
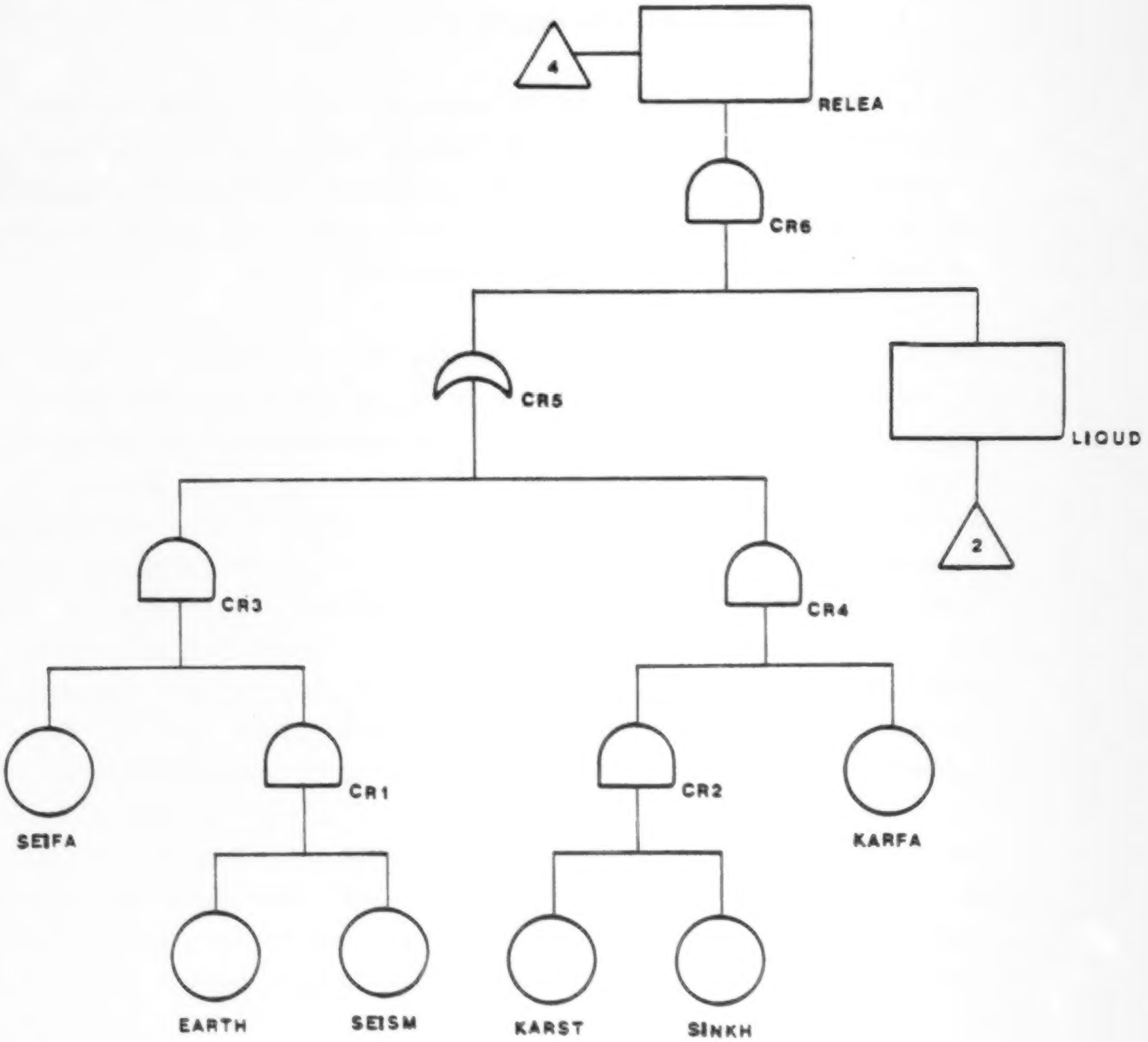

4
RELEA
IO1
8
INSRE
REDFR
IO2
EVNOC
EXEVR
BYPAS
CLOGT
INDRG
IOERR
EVENT

FIGURE A-23

CATASTROPHIC RELEASE


4
RELEA
CR6
CR5
LIQUD
2
CR3
CR4
SEIFA
CR1
CR2
KARFA
EARTH
SEISM
KARST
SINKH

- time-dependent probability distribution (triangular or time-dependent binomial)
- time-independent probability distribution (binomial)
- conditional events (which occur if events leading to them occur)
- performance related events

The latter type of event either is associated with a volume of liquid representing a contribution to the leachate budget, or a value that represents a proportion of leachate not removed by retrieval components, such as drainage and leachate collection systems. The type of distribution for each event is also specified in Table A-9.

Several comments should be made regarding the relationship of fault-trees to the simulation model. Because some of the event boxes are not associated with specific probabilities of occurrence, it is not possible to assign a probability to each event. Therefore, it is not possible to evaluate the probability of combinations of such events to determine the expected probability of the top event. This is primarily because certain events act as flow gates. For example, a certain proportion of leachate may not be captured by the leachate collection system, represented by the gate labelled LCSEF. This proportion will vary according to the degree of integrity of the liner material below it. A breached liner will result in a lower collection efficiency in the overlying leachate collection system. It is therefore difficult in the model to evaluate all of the components in the scenarios using the traditional fault-tree technologies. In short, there are provisions in the model code to handle valve and threshold events that differ slightly from the relationships described by the fault-trees. These will be discussed in greater detail in a later section.

A second difficulty in modelling the fault-trees involves the manner in which they are linked. It is not realistic, for example, to evaluate each fault-tree (failure scenario) separately from base to top and then proceed to the next fault-tree, since different events can effect the same result. An example is the rupture of a clay or synthetic liner (TEARS). This event can occur through damage to the liner during installation (if synthetic), burrowing by animals, material aging, upward hydrostatic pressure from a fluctuating groundwater table, or rupture in response to seismic or sinkhole collapse processes. As a result, parts of different fault-trees must be evaluated in order to determine whether the event TEARS actually occurs. An event may be evaluated several times in a given model run. This also precludes the possibility of evaluating each fault-tree separately and results in a fairly complicated model code.

Finally, the fault-trees represent failure from facilities which can exhibit a range of design configurations; for example facilities can be designed with one to three containment liners. Changes are made in the model code to reflect these conditions. In a triple-lined facility, the states of events, LINE1, LINE2, and LINE3 would be evaluated to determine whether any of the three liners are breached in a given iteration and benchmark period. In a single-lined facility, the states of events LINE2, and LINE3 would be automatically set to a failed state and only LINE1 would be evaluated for failure. Since all three events feed into an .AND. gate (Figure A-10), the event LINER would only occur if LINE1 is in a failed state. Again the model code may differ from the fault-tree diagrams in such cases.

3.3.2 Probability Distributions

Four types of probability distributions have been included in the failure analysis model to represent the basic and intermediate events in the fault-trees described previously. Table A-9 contains these distributions: triangular (time-dependent), lagged triangular, binomial distribution (time-independent), and the time-dependent binomial distribution. Each of these distributions will be described briefly.

Due to the lack of data regarding disposal facility component lifetimes and at the suggestion of EPA staff, it was assumed in this study that the probability of failure for time-dependent events be described as a linear function of time, that is a triangular distribution. The probability of failure for a component just installed is therefore zero, while the probability at a time corresponding to the useful life of the component is 1.00 (Figure A-24a). This has the somewhat undesirable consequence that events described by such distributions (e.g., aging of liners) are certain to occur given enough time. Efforts will be directed in the next phase of the study to replace some of these distributions with alternative statistical distributions.

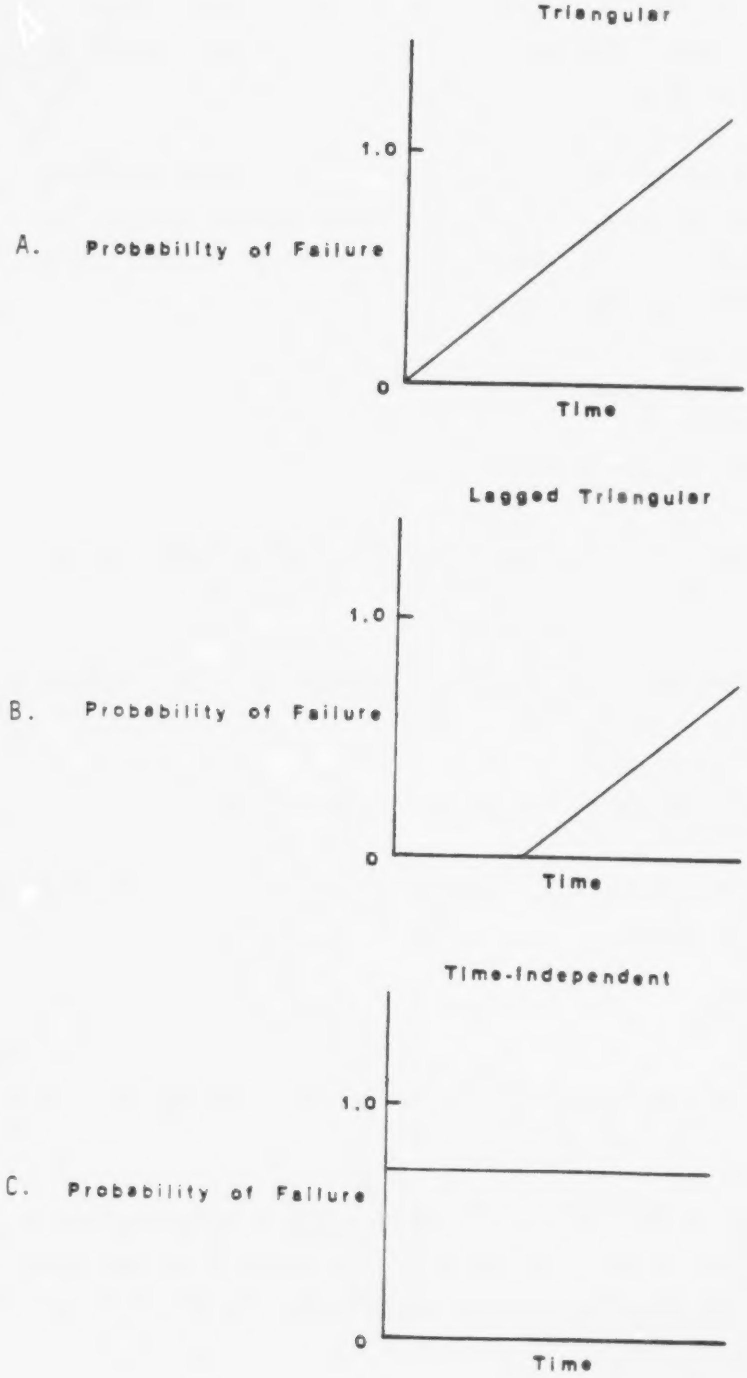
Lagged triangular distributions are merely triangular distributions that start at some time greater than zero (Figure A-24b). This type of distribution would describe events associated with components that are installed some time after the initial start of disposal operations, for example cover systems.

Some events occur in a constant proportion of the total number of cases and are independent of time (Figure A-24c). For example, failure due to seismic events occur only in areas subject to earthquakes and these areas represent a proportion of the total area of the country. These events were described in this analysis by a binomial distribution. This represents the probability that of a given number of trials, with two mutually exclusive outcomes, a certain number will result in one state while the remainder will result in the other.

In some situations, the probability of an event is a constant over a particular interval of time and the period of analysis is greater than that interval. For example, the probability of a 100-year flood event is by definition equal to 0.01 in any given year. However, the probability of at least one such event occurring in a 100-year period is much greater. The expression used to estimate the probability of an event occurring at least once during a period of n years is:

$$1-(1-p)^n$$

FIGURE A-24
PROBABILITY DISTRIBUTION TYPES



where p is the probability of occurrence during a single year. It was decided to focus only on the first occurrence of these events. The probability of failure due to the multiple occurrence of such events will be explored in the next phase of this study.

In certain cases, an event could conceivably be represented by either a time-dependent binomial distribution or a triangular distribution. The distribution types were selected, somewhat subjectively, on the basis of the original data describing the events.

The probability distributions are sampled in the following way:

- Binomial distribution with probability p

    1. A random number in the range 0 to 1 is selected from a random number generator

    2. If the random number is less than p, the event occurs, otherwise it does not

- Time-dependent binomial distribution with probability p

    1. Calculate the probability, Pr, that the event occurs once within the benchmark period, n

       $Pr = 1-(1-p)^n$

    2. If the random number is less than the probability Pr, the event occurs

    3. If the event occurs, the year of occurrence is selected from a random uniform distribution, with a lower bound 0 and an upper bound equal to the time at which the probability (Pr) of the event occurs is .99.

- Time-dependent triangular distribution with time to failure parameter M

  1. A random number in the range 0 to 1 is selected

  2. The year (t) that the event occurs is determined by finding the intersection of the ordinate value (value of the random number) and the triangular distribution (Figure A-25). The time, t, is located directly below the intersection point on the function.

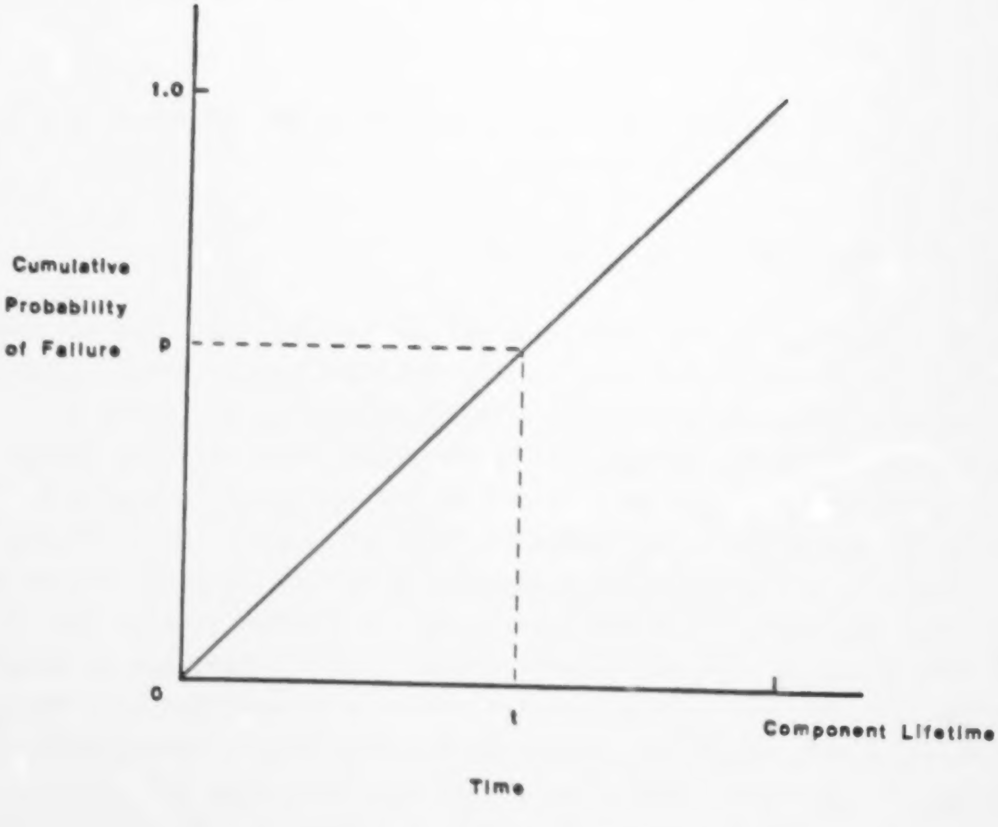
  3. Compare the year of occurrence t, to the benchmark period. If t is less than M, the event occurs.

  4. An analogous procedure is used for events described by a lagged triangular distribution.

3.3.3 Monte Carlo Simulation Model

The evaluation of the fault-trees was facilitated with a computerized Monte Carlo simulation model, specifically developed for the study. This enabled us to estimate the probability of system failure given various facility designs, climatic settings, and waste stream characteristics. Monte Carlo simulation is a technique that permits the incorporation of stochastic elements into fault-tree analysis. Uncertainty about the timing and frequency of the events in the fault-trees exists because: (1) some events are probabilistic in nature (earthquake and flooding events), and (2) others are not well understood (service lives of liners due to aging). The Monte Carlo model enables selected events to be described by probability distributions which are sampled and then evaluated to determine which events occur over a given time frame. The fault-trees are then evaluated in terms of the states of all of the events (whether they occur or don't occur) and the relationships between them, as described by the logic gates. In this way, the status of the top event is determined, that is whether release occurs or not. The above steps are repeated several thousand times

FIGURE A-25. DETERMINATION OF A COMPONENT TIME-TO-FAILURE FROM A TRIANGULAR DISTRIBUTION



and each time the probability distributions are resampled and the states of the events are reevaluated. It is as if several thousand different facilities of similar design were being evaluated for their performance. The total number of facilities which fail divided by the total number of iterations determines the expected probability of failure for a given facility type, benchmark time and climatic regime.

The model provides the flexibility to easily modify the probability distributions for selected events and in so doing to evaluate the effect of a given set of component reliability assumptions upon the uncertainty of the system performance estimates. For example, it is very simple to change the effective time to failure for major components and to determine their relative contribution to overall system performance. Similarly, assumptions about the locational characteristics of the facilities and design configurations can be modified merely by changing the probability parameters for pertinent events.

Finally, the model permits the evaluation of not only the expected value but the variance of leachate release volumes from the hypothetical facility population.

3.3.4 Model Structure

A flow chart describing the operation of the simulation model is shown in Figure A-26. The input requirements for the model include:

- Design specifications and locational characteristics for the hypothetical facility population

- Distributions describing the probability of occurrence for events in the fault-trees. The distributions are based upon data collected in the literature review and on engineering analysis. The distribution types and parameters for the events in the fault-trees are listed in Table A-9.

MONTE CARLO
SIMULATION MODEL
FLOW CHART

FIGURE A-26

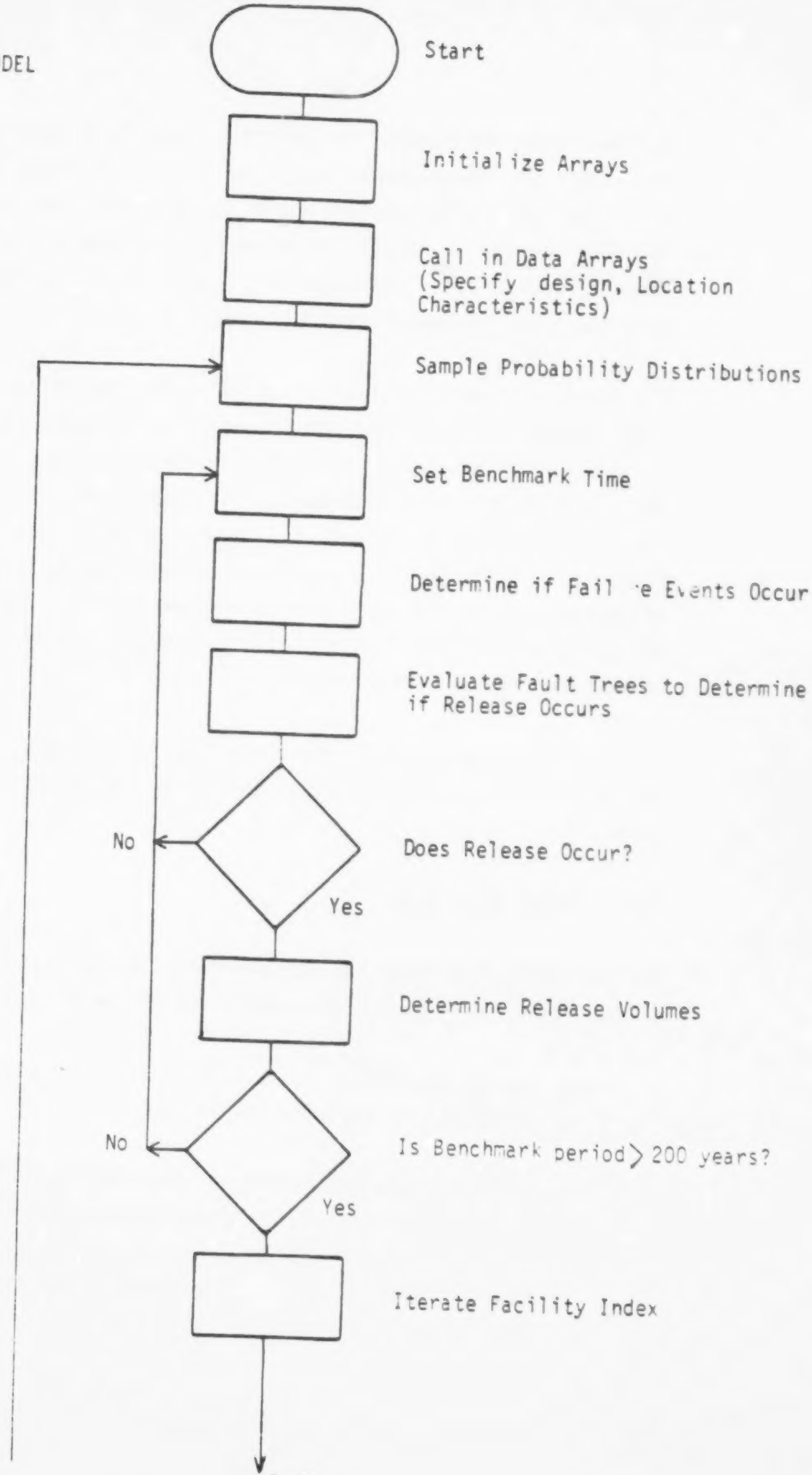
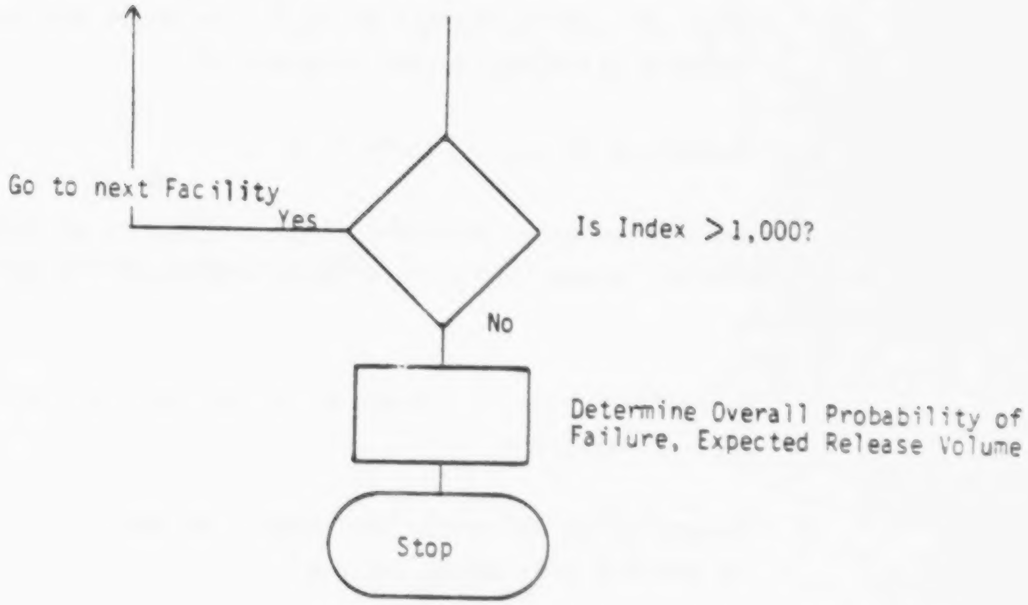

Start
Initialize Arrays
Call in Data Arrays (Specify design, Location Characteristics)
Sample Probability Distributions
Set Benchmark Time
Determine if Failure Events Occur
Evaluate Fault Trees to Determine if Release Occurs
No
Does Release Occur?
Yes
Determine Release Volumes
No
Is Benchmark period > 200 years?
Yes
Iterate Facility Index

FIGURE A-26 (Continued)


Go to next Facility
Yes
Is Index >1,000?
No
Determine Overall Probability of Failure, Expected Release Volume
Stop

- Hydrologic input volumes defined as random uniform distributions describing contributions to the leachate budget from precipitation, flood waters, and groundwater fluctuations

- Other performance-related parameters including drainage and leachate collection system efficiencies

- Number and timing of benchmark periods

Several steps are performed to determine the probability of system failure for each disposal design in a given climatic regime and for each fault-tree:

- A benchmark time is selected for which the likelihood of failure will be estimated

- Determine for all events described by probability distributions if and when such events occur

- Assign a value of one to each event which has occurred, zero to the remaining events

- Evaluate the fault-tree by determing the status of each logic gate in the tree, for example:

    1. .AND. gate: the event resulting from the gate occurs if all input events to the gate are equal to one

    2. .OR. gate: the event resulting from the gate occurs if any one of the input events to the gate is equal to one

- Determine if the top event has occurred

- If the top event has occurred, determine the volume of leachate released (see next section)

- Repeat the process 1000 times, using a separate set of random numbers each time

- Determine the probability of failure and expected release volume

The number of simulations selected for a given scenario was chosen on the basis of the probabilities of the events comprising the failure model and cost considerations. Many of the events described with a binomial distribution have a probability of 0.001 or less. This suggests that, on average, 1000 simulations would be required for such an event to occur once in a set of runs. A greater number of runs would be required to include less frequent events (such as seismic events), but at considerably greater cost. Preliminary testing with the model indicated that runs made with few simulations resulted in inconsistent failure probability estimates. It was decided that at least 1000 simulations would suffice in order to include the majority of failure events in the model runs and achieve consistent results.

3.4 Hydrologic Balance Analysis

The simulation model was designed to incorporate mass balance techniques such that the flow of liquid into and from the disposal system could be estimated, at the same time that the proportion of facilities which fail is determined. In this manner, the liquid balance and fault-tree analyses are considered to be parallel.

The events in the fault-trees include those which represent inputs to the liquid budget in the disposal system (net infiltration, flood waters, groundwater, free liquids) liquids removed from the system (drainage and leachate collection systems), and those that result in permanent storage of leachate (clay liners).

The overall structure of the hydrologic balance calculations is indicated in Figure A-27. The following steps are implemented for a given iteration and a given benchmark period in the simulation model:

FIGURE A-27
HYDROLOGIC BALANCE FLOW CHART

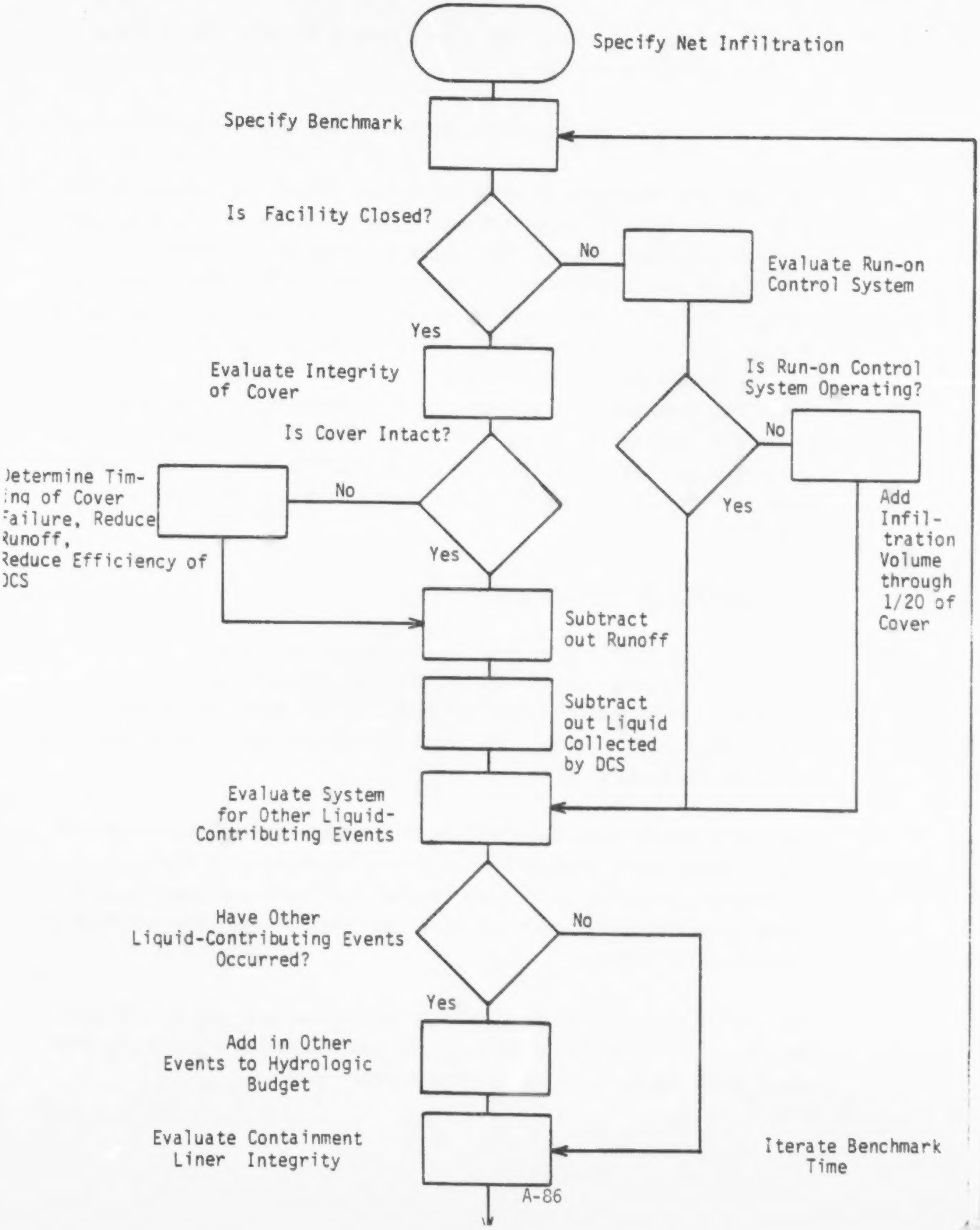
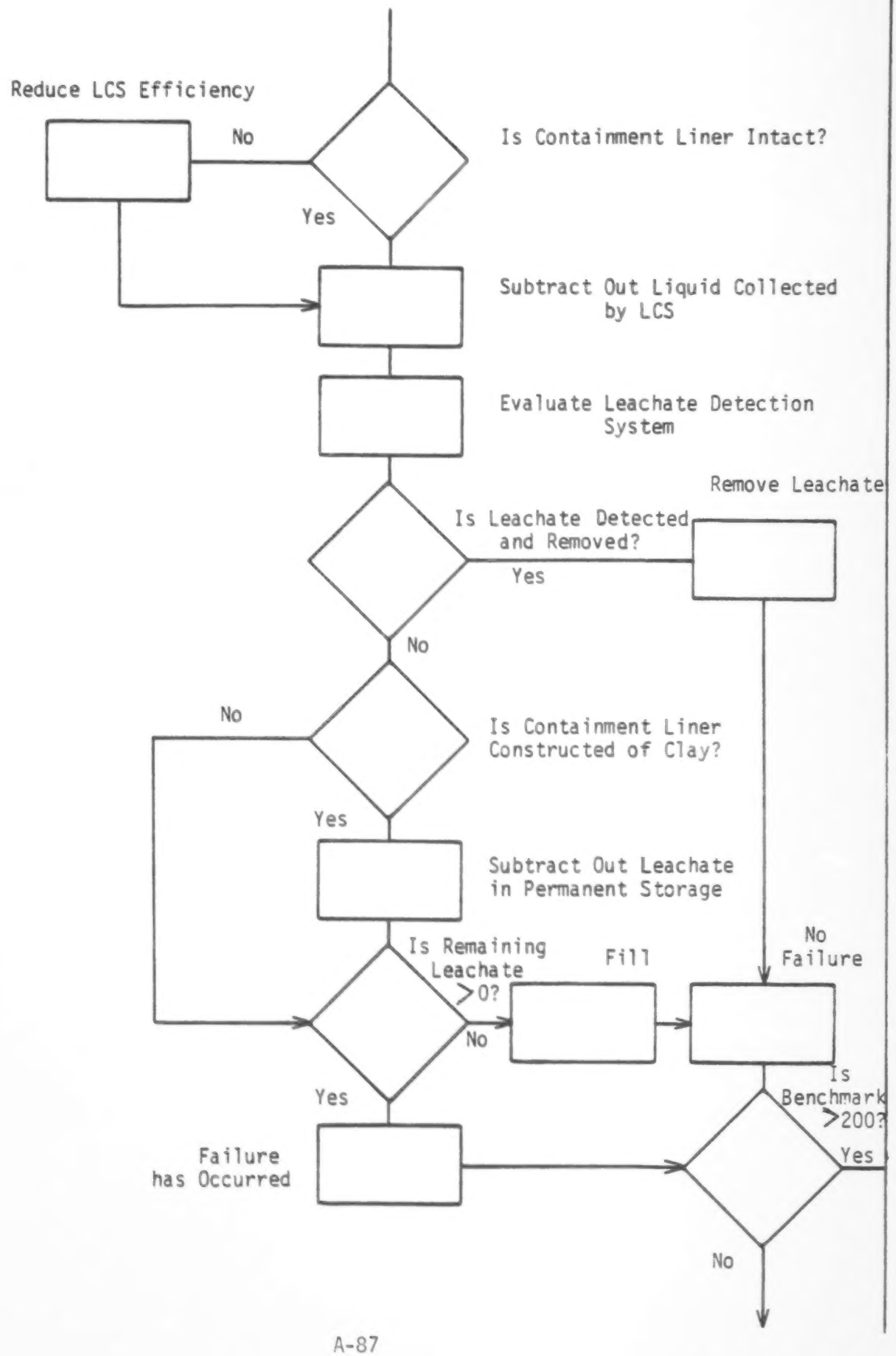
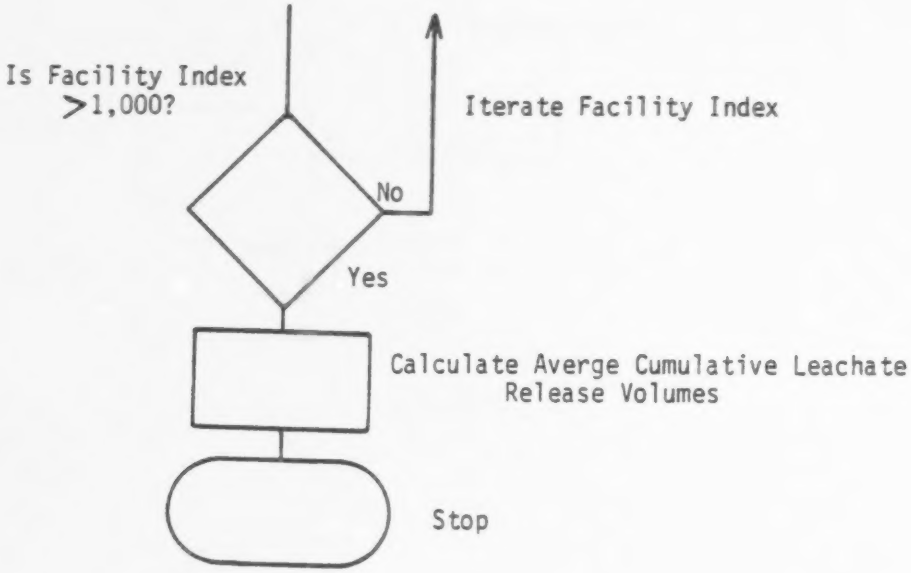

Specify Net Infiltration
Specify Benchmark
Is Facility Closed?
No
Evaluate Run-on Control System
Yes
Evaluate Integrity of Cover
Is Run-on Control System Operating?
Is Cover Intact?
No
etermine Tim-
ng of Cover
ailure, Reduce
unoff,
educe Efficiency of
CS
No
Yes
Add Infil-tration Volume through 1/20 of Cover
Yes
Subtract out Runoff
Subtract out Liquid Collected by DCS
Evaluate System for Other Liquid-Contributing Events
Have Other Liquid-Contributing Events Occurred?
No
Yes
Add in Other Events to Hydrologic Budget
Evaluate Containment Liner Integrity
Iterate Benchmark Time

FIGURE A-27 (Continued)



Reduce LCS Efficiency
No
Is Containment Liner Intact?
Yes
Subtract Out Liquid Collected by LCS
Evaluate Leachate Detection System
Remove Leachate
Is Leachate Detected and Removed?
Yes
No
No
Is Containment Liner Constructed of Clay?
Yes
Subtract Out Leachate in Permanent Storage
Is Remaining Leachate >0?
Fill
No Failure
No
Yes
Is Benchmark >200?
Yes
Failure has Occurred
No

FIGURE A-27 (Continued)


Is Facility Index
>1,000?
Iterate Facility Index
No
Yes
Calculate Averge Cumulative Leachate
Release Volumes
Stop

- Specify net infiltration and multiply by duration of time (up to benchmark period) and area of facility

- Compare benchmark time to time of closure

- If benchmark is less than time of closure (i.e., <20 years) evaluate appropriate fault-trees to determine whether infiltration enters active cell due to inadequate run-on control measures (if so add 1/20 of net infiltration volume to budget)

- Subtract out fraction of infiltration due to runoff (95% if cover intact, 60% if cover has cracks)

- Subtract out fraction of remaining infiltration to represent liquid captured by drainage collection system (†99% for intact covers, 79% for breached covers)

- Evaluate fault-trees to determine if other inputs to hydrologic budget occur (groundwater fluctuation, flooding, etc.)

- Evaluate fault-trees to determine if liner failure has occurred

- Subtract out fraction of total remaining budget to represent leachate captured by leachate collection systems (varies from 99% for intact liners to 40 - 75%, depending on liner permeability for breached liners)†

- If benchmark time is greater than the post-care period (>50 years) no leachate is collected in retrieval systems

- Subtract out volume of leachate representing permanent storage in clay liner

† These percentages are equal to 100% - efficiency of the collection system.

- If remaining leachate budget is greater than zero, then failure has occurred and leachate volume is equal to leachate budget.

These steps are repeated for each benchmark period and for all iterations in a simulation run. Average leachate release volumes are calculated for each benchmark period.

The hydrologic input volumes for a particular facility were chosen from a series of random uniform probability distributions, representing the likely range of volumes based on engineering analysis. For example, the net infiltration volume is drawn from a uniform distribution with a lower bound of zero and an upper bound equal to the annual net infiltration (see discussion of climatic regimes in section 4.1). The hydrologic input parameters are listed in Table A-10 and are referenced by the labels used in the fault-trees. The technologies to which they apply, the assumptions used to estimate the bounds of the input volume distributions, and the range of liquid volumes in cubic meters are also listed. Some of the inputs are "one-shot" additions of liquid to the hydrologic budget, others occur over a duration of time.

For example, the duration of infiltration through failed covers and flow through containment liners are tied to the times at which these components fail. For example if a cover fails at year 40, and a simulation is run for a benchmark period of 50 years, then the total flow through the cover would be given by the following:

Total Volume = 20 x flow rate during pre-closure +
(40-20) x flow through intact cover +
(50-40) x flow through breached cover

where the start of the post-closure period is at year 20. Different mechanisms may result in cover failure at different times. In such cases, the one that occurs first is used to define the initiation of failure. Different runoff and drainage collection efficiencies would be used to

TABLE A-10. HYDROLOGIC INPUT PARAMETERS FOR FAILURE ANALYSIS RUNS

INPUT LABEL	TECHNOLOGY		ASSUMPTIONS	RANGE OF HYDROLOGIC INPUT VOLUME (m^3) UPPER BOUND VALUES †
	LF	SI		
1. BYPAS		0	(Operating depth of 2nd impoundment-freeboard) x area	3.7×10^3
2. CATRL		0	Area x operating depth	2.1×10^5
3. CLOGT		0	Average rainfall + inlet flow for 7 days-freeboard volume	3.6×10^5
4. DAMAG		0	Leakage through 1% of liner, unit gradient, subgrade permeability = 1×10^{-5}cm/s, duration = simulation length	$0 - 6.1 \times 10^4$
5. EXEVR		0	Maximum probable rainfall for 24-hour period - freeboard x area	$0 - 1.1 \times 10^4$
6. FFILL (SPILL)	0	(0)	Area x depth of fill (LF), area x height of berm (SI), area x (fill + cover) x specific retention for post-closure events	5.9×10^4
7. FLVOL (SPILF)	0	(0)		
8. FREEL	0		Operating depth x area x specific retention (LF)	9.1×10^3
9. INADD		0	Leakage estimated using Darcy's Law, head = operating depth, variable duration-depends on breakthrough time,effective porosity = 0.1, capillary head=-10cm	6.1×10^{-1} - 3.9×10^6
10. INDRG		0	See CLOGT	
11. LINER		0	Leakage through 10% of liner, unit gradient, subgrade permeability = 1×10^{-5}cm/s, variable duration, depends on timing of liner failure	See Text

† Lower bounds for distributions are equal to zero. A range of upper bound values implies that different designs are assigned different maximum input volumes.

TABLE A-10 (Continued)

12. RAINF	0	0	Area x mean annual infiltration (precipitation - evaporation), depends on timing of cover placement and timing of cover failure	See Text
13. TDISS		0	Leakage through 10% of liner, unit gradient, subgrade permeability = 1×10^{-5}cm/s, 7 day-duration	5.9×10^3
14. TEARS		0	Leakage through a single hole (size depends upon liner material), unit gradient, subgrade permeability = 1×10^{-5}cm/s, variable duration, depends on timing of liner failure	See Text
15. UNDER	0 (post-closure)	0	(Active fill + cover) x area x specific retention, may be location dependent	5.7×10^4
16. WEARS		0	See DA[illegible]S	

describe flow through the intact and breached covers. These values are based upon EPA guidance documents describing the design of disposal facility covers and theoretical analyses of collection system efficiencies by Kmet, et al (1981).

Several time-dependent leachate volumes are included in the simulation model for surface impoundments. These include seepage due to inadequate thickness (INADD) and leakage due to material aging (LINER). The upper bound for the input distribution describing slow leakage through a liner is calculated by using a Darcy flow law. First, the time for the liner to saturate is determined:

$$\text{Time to Saturation} = \frac{\text{liner thickness}}{(\text{permeability})\left(1+ \frac{\text{operating depth - capillary head}}{\text{liner thickness}}\right)(\text{effective porosity})}$$

$$\text{Volume of leachate} = (\text{Facility area})(\text{20-time to saturation in years}) \times \left(1 = \frac{\text{operating depth - capillary head}}{\text{liner thickness}}\right)$$

Head conditions are assumed to be constant while the impoundment is filled with liquid. The lower boundary is characterized by a constant negative head (-.1m) representing the effects of capillary forces. Seepage through synthetic liners was assumed to occur throughout the entire pre-closure period at a rate equal to the permeability of the liner. The total volume for synthetic liners is then given by:

$$\text{Volume} = (\text{20 years})\ (\text{permeability})\ (\text{facility area})$$

Releases due to leaks resulting from liner aging were calculated with the following expression:

Volume = (10% of facility area) (permeability of subgrade) x
(unit gradient) (20 years - time to failure)

The permeability value for the subgrade materials was assumed to equal 1 x 10^{-5} cm/sec. To determine the specific input volume for a particular iteration, a number would be selected from a uniform distribution with a lower bound equal to zero and an upper bound equal to the product of the first three terms in the above expression. This number would then be multiplied by the time over which failure of the liner occurs (the difference in years between the end of the pre-closure period and the time of liner failure calculated in the fault-tree analysis).

3.5 Assumptions Used in the Failure Analysis

Various simplifying assumptions were made to facilitate the operation of the failure analysis model and the estimation of release rates and durations. Perhaps the most significant assumption used in the model consists of the reliability estimate for clay and synthetic containment and cover liners. As discussed previously, these events are described by triangular distributions that result in very low component failure rates in early benchmark periods and insure that these components fail within 35 to 55 years after the start of disposal operations. This strongly controls the overall performance of the system, since leaks in the cover caused by liner aging result in increased infiltration to the fill area and leaks in the containment liners result in release of leachate from the facility. Suggestions have been made in the course of the peer review process to replace the triangular distributions with alternatives (such as Weibull or normal functions) so that system failure would not necessarily be assured by any particular benchmark period.

It has also been suggested that aging of clay cover liners (which are not in contact with wastes) is not a realistic failure mechanism. It is our understanding that clay covers, like any other soil material exposed to near-surface conditions, is subject to seasonal changes in moisture content, in many cases to freeze/thaw processes, and to the penetrating effects of vegetation and soil organisms. These processes as a whole will effect the development of cracks in a clay liner and thus reduce its integrity. Although the time frame over which these processes operate may be uncertain, it is believed that these factors would occur at actual facilities. As a result, we have included a scenario representing the aging of cover liners.

The magnitude of the hydrologic inputs were determined from a series of uniform random distributions which are defined by lower and upper bound volumes. The volumes are heavily dependent upon the area of the facility, and as a result, release volumes are expected to be a linear function of area. The probability of failure, however, is not a function of facility size, but is nearly constant for a given climatic regime and benchmark period. Limited experimentation with the failure model applied to different sized facilities suggests that both assumptions are valid. This is important because it obviates the need to make separate runs for each class of facility size.

Incipient infiltration during the active life of a landfill facility (the first 20 years) was assumed to be 1/20 of the mean annual infiltration of the entire facility area for a particular climatic region for facilities with inadequate run-on control measures. This was based upon operating schedules at hazardous waste facilities which typically open and close a single cell within a short period of time in order to minimize leachate generation. This was assumed to coincide with the placement of a final cover over filled sections of the facility and was chosen to be one year. However, all portions of the cover system were assumed to start "aging" at year 20 of the simulations. This suggests that the reliability of the portions of the cover (particularly those installed soon after the facility is opened) will be over-estimated. This assumption will result in underestimation of failure percent and release rate.

Net infiltration is assumed to be a constant for a given facility for all benchmark periods. In reality, precipitation and evaporation rates would vary from year to year. The hydrologic volume associated with infiltration is a random uniform distribution with a lower bound of zero inches and an upper bound equal to the net annual infiltration. Effectively, this means that the average net infiltration value is equal to approximately half of the infiltration value for a given climatic regime. Again, this assumption will result in underestimation of release rates in the hypothetical facilities compared to actual facilities.

An important assumption applied to facilities which incorporate a leachate detection system is that ameliorative actions will be taken by the operator if the system is activated. Such an action is required by the design and performance standards for disposal systems set forth in the RCRA regulations. This would entail excavation of the site, repair of breaches in the liner, and pumping of any leachate in the detection layer. Therefore, operable leachate detection systems at selected facilities are assumed to reduce leachate release at least through the post-closure period.

Operators were assumed to maintain their facilities only through the post-closure period, as required by the RCRA regulations. Consequently, no long-term inspections, collection of leachate or drainage, operation of flood pumps, nor response to leachate detection systems are assumed to take place after the 50-year benchmark. This generally resulted in a dramatic increase in failure percent shortly after the inception of the post-care period.

Some of the events (particularly those described by time-dependent binomial distributions) can occur in any one year and could conceivably occur more than once during the lifetime of a facility. Since the failure analysis does not yet incorporate repairs or replacements to failed components, it was decided to focus only on the first occurrence of multiple events. In the case of events described by time-dependent binomial distributions, this time of occurrence was calculated by sampling from a uniform distribution representing the time period required to attain a probability of occurrence of 0.99. This procedure provides for consistent estimates across alternative benchmark periods.

Additional assumptions made in the analysis include the following:

- No permanent storage of infiltration in the cover.
- Permanent storage of leachate in clay liners.
- Waste to fill ratios are 70:30 in landfills.
- Waste and intermediate fill materials are assumed to be emplaced with moisture contents equal to field capacity.
- Complete and instantaneous mixing of infiltration and waste constituents.
- Inhomogenities in the waste materials promote "channelling" of infiltration from the cap to the bottom of the active fill zone.
- Waste materials are left in place in surface impoundments and closed as landfills.
- Waste constituents captured by leachate collection systems are "recycled" to disposal areas.
- Facilities are shaped like rectangular blocks.
- Design dimensions for the technologies are equivalent to those specified in the failure analysis study conducted by the Land Disposal Branch of the Office of Solid Waste (97,126m^2 by 6m deep for landfills and 97,126m^2 by 2.1m deep for surface impoundments).

Much of the proposed effort in the next phase of the Liner Location project will be directed towards refining the assumptions above to reflect more realistic operating and design characteristics at the hypothetical facilities.

3.6 Limitations

Several sources of error contribute to considerable uncertainty of the failure rate and release volume estimates generated with the failure model. The largest source of error results from the inadequacy of the data base describing the reliability of land disposal facilities. Very few hazardous waste facilities have been designed and constructed, much less monitored for their performance. Nonetheless, an extensive body of resources, including published reports, vendor guarantees, and engineering analyses were used in the study. Best engineering judgment was used when necessary to estimate component failure rates and the impacts of these failures on other components and overall system performance.

The major component of these systems, clay or synthetic liners and drainage and leachate collection systems, are only now being tested in actual operational settings. Although synthetic liners have been used in water reservoir applications for up to 50 years, their long-term effectiveness in more aggressive chemical environments has not been proven. A recent report by the Office of Solid Waste, Land Disposal Branch (Arthur D. Little, 1983) suggests that various synthetic liner materials may attain useful service lives ranging from 20 to 150 years. Because liner vendors rarely provide product guarantees of more than 20 to 30 years, we have selected a value for liner lifetime of 35 years in this study.

It is possible that specific liner materials may have longer service lives, and only continued long-term testing of such material will produce more accurate assessments of liner longevity. To analyze the effect of such uncertainty in the model, we performed a rudimentary sensitivity analysis on selected disposal designs by increasing the time to failure for liners in the cover and containment systems. Markedly different system failure rates were obtained. For example, in a landfill with a double synthetic liner and a net infiltration of ten inches, the failure rate dropped from 98 percent at 100 years to 27 percent when liner lifetime was increased to 150 years. Because the failure model contains a large number of components, each of which is described by a reliability parameter of uncertain accuracy, the effects of these combined uncertainties could be considerable.

Another factor to which the model results are sensitive, is net infiltration simulations conducted with zero and 1-inch net infiltration values showing significantly different failure rates (much higher in the latter category). This suggests that even a small volume of infiltration will result in a reduced level of performance. Facilities that are located in regions with a negative annual infiltration budget (based upon average precipitation and evaporation values) may nonetheless experience short-term periods of positive net infiltration that would result in system failure. Furthermore, the efficiencies of drainage and leachate collection systems have been estimated by theoretical considerations. They have not been investigated to a great extent in actual transient field conditions nor in conjunction with degrading liner systems. Uncertainties in estimating actual net infiltration and leachate collection system efficiency also compound the difficulties of predicting overall system performance.

Errors in failure rate and release volume are also caused by the inherent variation of stochastic models. The failure model selects from a series of probability distributions in order to specify the timing of component failures. The probability distributions are supplied by means of a random number generator which is "initialized" through a random number seed. The choice of a different seed can result in different time-to-failure estimates, and hence different over-all failure rates. Sensitivity runs were conducted by varying the value of the random number seed. Failure rates for comparable designs, location specifications, and benchmark times tended to vary by one to two percent in these runs.

Release volumes are quite sensitive to failure rates and were found to vary by ten to 25 percent for comparable facilities with low failure rates. Release rates of facilities that exhibit failure rates in the range of 0.05 to one percent (for example, those in arid regions or with low benchmark times) are based upon the average of only a few facilities. The volume of a single contributing hydrologic input can vary over several orders of magnitude. Therefore, the variability of total release volumes between two simulations that differ by only a few failure episodes can be considerable.

These observations underscore the importance of collecting as much component reliability data from existing disposal facilities as possible in order to refine the estimates of system performance. Continued sensitivity analyses with the model can be used to highlight the most critical components in disposal facilities and to dictate further research efforts.

4. RESULTS

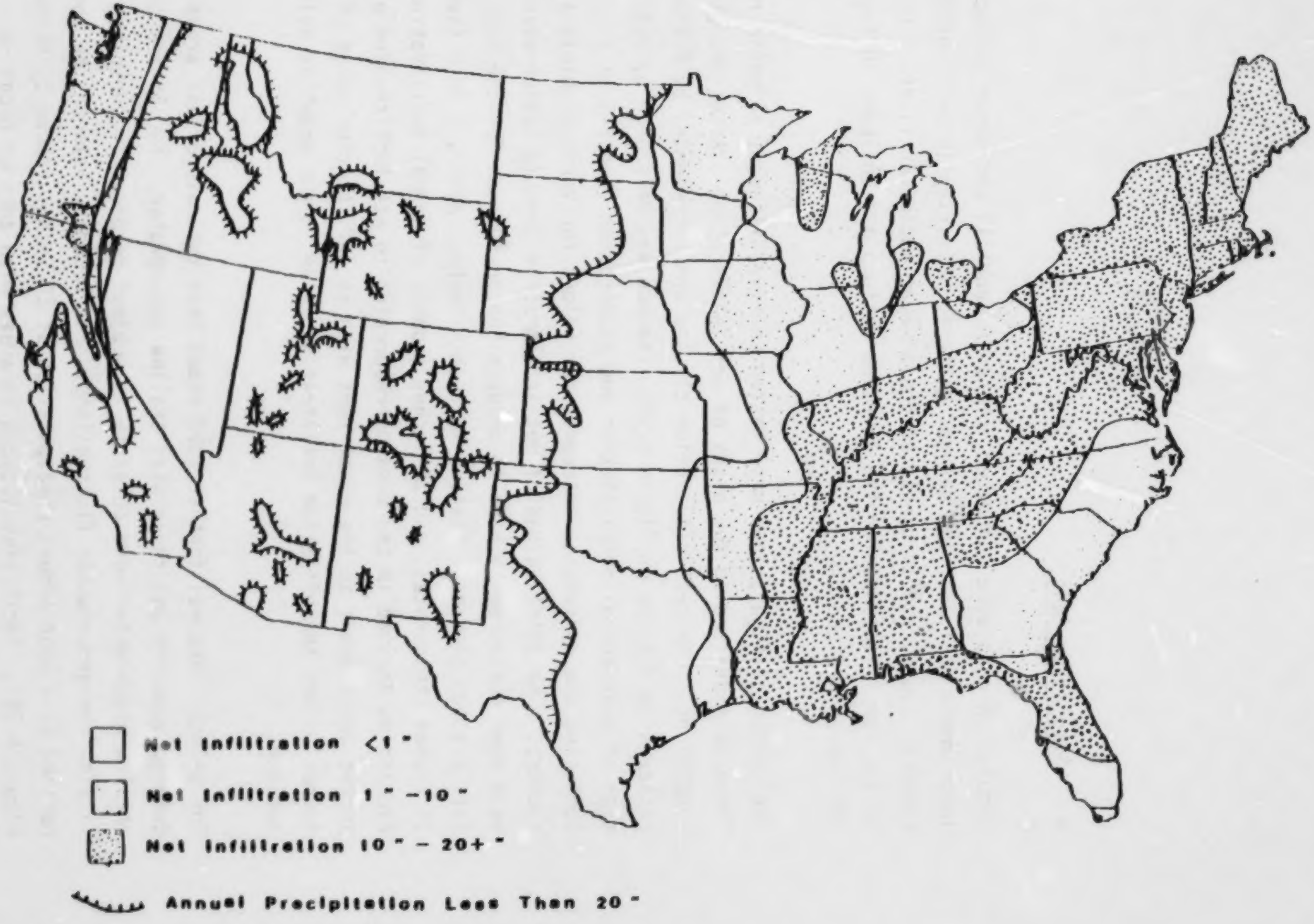
4.1 Simulation Runs

Simulation runs were conducted for seven landfill and seven surface impoundment designs. The designs differed primarily in terms of the numbers, types, and thickness of containment and cover liners. Detailed design specifications for the fourteen designs are included in Figure A-6 and Tables A-1 and A-2.

The design configurations were tested in five different climatic regions. These were defined on the basis of net infiltration classes and groundwater conditions. The net infiltration classes are represented by different patterns on the map on Figure A-28. The map was developed by overlaying maps of mean annual precipitation and evaporation (Linsley et al, 1975) and computing the difference between these values for various points in the country. The point values of net infiltration (precipitation-evaporation) were then contoured by hand to produce the boundaries for the net infiltration classes. Classes include 0 inches (arid), 1 inch (semiarid), 10 inches (temperate), and 20 inches (humid) of annual infiltration. Facilities located in the area corresponding to net infiltration of 1-10 inches corresponds to the model runs with an infiltration value of 10 inches (since the effective infiltration value in the model is half the maximum).

The 1-inch class was further subdivided into two categories: areas with deep groundwater and those with shallow groundwater. Facilities overlying shallow groundwater were potentially subject to periodic contributions of liquid from groundwater fluctuations. The boundary between the two is defined by a mean annual precipitation of 20 inches (shown by hachures on Figure A-28). Facilities located in areas with zero or negative infiltration and those with 1 inch of infiltration and less than 20 inches of precipitation were assigned to the deep groundwater category. All others were assumed to be above shallow groundwater.

FIGURE A-28. MAP OF NET INFILTRATION CLASSES


Net Infiltration <1"
Net Infiltration 1" -10"
Net Infiltration 10" - 20+"
Annual Precipitation Less Than 20"

Two sets of waste stream characteristics were incorporated in the simulation runs. One set assumed that a small percentage of facilities experienced failure due to incompatible waste/component reactions (for example, breach of containment liners and loss of leachate storage capacity in clay liners). The second set assumed that all facilities experienced incompatible waste/component reactions.

4.2 Simulation Results

For each design, climatic category, and waste scenario, the failure probability and release volumes were determined at seven benchmark times (Tables A-11 and A-12). The probability values in the tables represent the proportion of all facilities that underwent one or more failures (scenarios) during the benchmark period. The leachate volume is an average of releases from all failed facilities for the time period up to and including the benchmark year. In order to calculate average annual releases, we used the following procedure:

1. Select failure percent criteria and time to failure.

2. Multiply failure percent by number of iterations/100. to obtain number of failed facilities at a given benchmark.

3. Multiply average cumulative release rate by the number of failed facilities in (2) to obtain total cumulative release volume.

4. Subtract from the total cumulative release volume in (3), the cumulative release volume from the previous benchmark to obtain the incremental release volume.

5. Divide the incremental release volume in (4) by the number of failed facilities in (2) (or the total number of facilities, if a weighted release is calculated) to obtain the average incremental release volume.

TABLE A-11. PERCENT FAILURE AND RELEASE VOLUME BY DESIGN, BENCHMARK TIME, AND CLIMATIC REGIME

LANDFILL	Benchmark Time						
	5	10	20	35	50	100	200
DESIGN 1							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1 (DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	82.0 .2094E+05	93.8 .6997E+05
P=1 (SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	90.2 .2288E+05	96.4 .7192E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	98.7 .2445E+06	99.5 .7321E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	99.4 .4879E+06	99.7 .1462E+07
DESIGN 2							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1 (DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	24.2 .6608E+04	73.9 .5507E+05
P=1 (SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	32.1 .8673E+04	76.9 .5742E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	92.3 .2312E+06	97.8 .7155E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	96.9 .4710E+06	98.6 .1447E+07
DESIGN 3							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1 (DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	24.2 .6617E+04	73.9 .5588E+05
P=1 (SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	32.1 .8679E+04	76.9 .5742E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	92.3 .2312E+06	97.8 .7155E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	96.9 .4710E+06	98.6 .1447E+07
DESIGN 4							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1 (DEEP)	0.0 .0	0.0 .0	0.0 .0	4.3 .5328E+02	4.3 .6578E+03	46.5 .1133E+05	82.3 .6172E+05
P=1 (SHALLOW)	0.0 .0	0.0 .0	1.5 .3054E+05	17.3 .1566E+05	26.8 .1885E+05	70.2 .3338E+05	90.3 .8218E+05
P=10	0.0 .0	0.0 .0	1.5 .3054E+05	17.3 .1584E+05	28.8 .2056E+05	96.7 .2579E+06	98.0 .7619E+06

TABLE A-11 (Continued)

```
 =20
            0.0       0.0       1.5      17.3      31.8      98.2      99.6
        .0        .0        .3054E+05 .1605E+05 .2253E+05 .5129E+06 .1512E+07
ESIGN 5
 P=0
            0.0       0.0       0.0       0.0       0.0       0.0       0.0
        .0        .0        .0        .0        .0        .0        .0
 P=1(DEEP)
            0.0       0.0       0.0     100.0     100.0     100.0     100.0
        .0        .0        .0        .8602E+01 .2248E+03 .2560E+05 .7587E+05
 P=1(SHALLOW)
            0.0       0.3       5.9     100.0     100.0     100.0     100.0
        .0        .6495E+04 .1307E+05 .7747E+04 .1244E+05 .4572E+05 .9975E+05
 P=10
            0.0       0.3       5.9     100.0     100.0     100.0     100.0
        .0        .6495E+04 .1307E+05 .7827E+04 .1448E+05 .2750E+06 .7796E+06
 P=20
            0.0       0.3       5.9     100.0     100.0     100.0     100.0
        .0        .6495E+04 .1307E+05 .7915E+04 .1675E+05 .5291E+06 .1533E+07
 ESIGN 6
 P=0
            0.1       0.5       0.8       1.1       1.1       1.1       1.1
        .4500E+04 .5216E+04 .4863E+04 .5017E+04 .5017E+04 .5017E+04 .5017E+04
 P=1(DEEP)
            0.3       0.7       1.0     100.0     100.0     100.0     100.0
        .1369E+04 .3978E+04 .4333E+04 .1440E+04 .5065E+04 .3016E+05 .8034E+05
 P=1(SHALLOW)
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4640E+05 .4992E+05 .5172E+05 .2745E+05 .3308E+05 .5817E+05 .1084E+06
 P=10
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4717E+05 .5048E+05 .5196E+05 .4186E+05 .7795E+05 .3278E+06 .8274E+06
 P=20
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4801E+05 .5111E+03 .5222E+05 .5560E+05 .1227E+06 .6266E+06 .1624E+07
ESIGN 7
  P=0
            0.1       0.5       0.8       1.1       1.1       1.1       1.1
        .4500E+04 .5126E+04 .4863E+04 .5017E+04 .5017E+04 .5017E+04 .5017E+04
 P=1(DEEP)
            0.3       0.7       1.0     100.0     100.0     100.0     100.0
        .1869E+04 .3978E+04 .4333E+04 .9550E+03 .1398E+04 .6161E+04 .1695E+05
 P=1(SHALLOW)
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4640E+05 .4992E+05 .5172E+05 .2897E+05 .2941E+05 .3418E+05 .4497E+05
 P=10
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4717E+05 .5048E+05 .5176E+05 .3703E+05 .4144E+05 .3886E+05 .1763E+06
 P=20
            1.3       3.5      16.7     100.0     100.0     100.0     100.0
        .4801E+05 .5111E+05 .5222E+05 .4396E+05 .5476E+05 .1495E+06 .3640E+06
SURFACE IMPOUNDMENTS
DESIGN 1
 P=0
            0.0       0.0       0.0       0.0       0.0       0.3       0.3
        .0        .0        .0        .0        .0        .1606E+06 .1606E+06
 P=1(DEEP)
            0.0       0.0       0.0       0.0       0.0      92.7      97.1
        .0        .0        .0        .0        .0        .2322E+05 .7415E+05
 P=1(SHALLOW)
            0.0       0.0       0.0       0.1       0.1      96.4      98.4
        .0        .0        .0        .7961E+04 .7966E+04 .2425E+05 .7516E+05
 P=10
            0.0       0.0       0.0       0.1       0.1      99.4      99.8
        .0        .0        .0        .8003E+04 .8049E+04 .2473E+06 .7518E+06
 P=20
            0.0       0.0       0.0       0.1       0.2      99.7     100.0
        .0        .0        .0        .8047E+04 .6278E+04 .4929E+06 .1499E+07
```

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TABLE A-11 (Continued)

```
DESIGN 2
 P=0
            0.0        0.0        0.0        0.0        0.0        0.3        0.3
          .0         .0         .0         .0         .0         .1390E+06  .1390E+06
 P=1(DEEP)
            0.0        0.0        0.0        0.0        0.0       31.3       78.7
          .0         .0         .0         .0         .0         .1036E+05  .3857E+05
 P=1(SHALLOW)
            0.0        0.0        0.0        0.0        0.0       35.4       80.8
          .0         .0         .0         .0         .0         .1080E+05  .5905E+05
 P=10
            0.0        0.0        0.0        0.0        0.0       94.3       98.0
          .0         .0         .0         .0         .0         .2308E+06  .7363E+06
 P=20
            0.0        0.0        0.0        0.0        0.0       97.0       99.0
          .0         .0         .0         .0         .0         .4772E+06  .1485E+07
DESIGN 3
 P=0
            0.0        0.0        0.0        0.1        0.1        0.4        0.4
          .0         .0         .0         .1409E+06  .1409E+06  .1411E+06  .1411E+06
 P=1(DEEP)
            0.0        0.0        0.0        0.1        0.1       33.9       79.4
          .0         .0         .0         .1409E+06  .1409E+06  .1092E+05  .5947E+05
 P=1(SHALLOW)
            0.0        0.0        0.0        0.1        0.1       36.7       81.1
          .0         .0         .0         .1576E+06  .1576E+06  .1143E+05  .5760E+05
 P=10
            0.0        0.0        0.0        0.1        0.1       94.3       98.0
          .0         .0         .0         .1576E+06  .1577E+06  .2312E+06  .7366E+06
 P=20
            0.0        0.0        0.0        0.1        0.1       97.1       99.0
          .0         .0         .0         .1577E+06  .1578E+06  .4770E+06  .1485E+07
DESIGN 4
 P=0
            7.1       11.0       21.2       21.2       21.2       21.2       21.2
          .9496E+05  .1335E+06  .1069E+06  .1069E+06  .1069E+06  .1069E+06  .1069E+06
 P=1(DEEP)
            7.1       11.0       21.1       21.3       21.4       39.0       72.6
          .7496E+05  .1335E+06  .1069E+06  .1065E+06  .1067E+06  .7999E+05  .9191E+05
 P=1(SHALLOW)
            7.1       11.0       21.2       31.6       32.1       49.6       79.5
          .9496E+05  .1335E+06  .1069E+06  .8710E+05  .8650E+05  .7836E+05  .9885E+03
 P=10
            7.1       11.0       21.2       32.2       36.9       93.8       97.7
          .9476E+05  .1335E+06  .1069E+06  .8683E+05  .8284E+05  .2658E+06  .7707E+06
 P=20
            7.1       11.0       21.2       32.5       42.3       96.6       78.9
          .9496E+05  .1335E+06  .1069E+06  .8773E+05  .8173E+05  .5165E+06  .1523E+07
DESIGN 5
 P=0
          100.0      100.0      100.0      100.0      100.0      100.0      100.0
          .5581E+04  .1557E+05  .3222E+05  .3222E+05  .3222E+05  .3222E+05  .3222E+05
 P=1(DEEP)
          100.0      100.0      100.0      100.0      100.0      100.0      100.0
          .5581E+04  .1557E+05  .3222E+05  .3235E+05  .3298E+05  .5748E+05  .1082E+06
 P=1(SHALLOW)
          100.0      100.0      100.0      100.0      100.0      100.0      100.0
          .5581E+04  .1557E+05  .3222E+05  .4690E+05  .4753E+05  .7202E+05  .1227E+06
 P=10
          100.0      100.0      100.0      100.0      100.0      100.0      100.0
          .5581E+04  .1557E+05  .3222E+05  .4801E+05  .5430E+05  .2981E+06  .8031E+06
 P=20
          100.0      100.0      100.0      100.0      100.0      100.0      100.0
          .5581E+04  .1557E+05  .3222E+05  .4925E+05  .6180E+05  .5487E+06  .1537E+07
```

TABLE A-11 (Continued)

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DESIGN 6							
P=0							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2000E+07	.2000E+07	.2000E+07	.2000E+07
P=1(DEEP)							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2002E+07	.2005E+07	.2030E+07	.2080E+07
P=1(SHALLOW)							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2016E+07	.2020E+07	.2044E+07	.2095E+07
P=10							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2028E+07	.2065E+07	.2307E+07	.2814E+07
P=20							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2042E+07	.2115E+07	.2602E+07	.3611E+07
DESIGN 7							
P=0							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2000E+07	.2000E+07	.2000E+07	.2000E+07
P=1(DEEP)							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2000E+07	.2001E+07	.2025E+07	.2076E+07
P=1(SHALLOW)							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2015E+07	.2016E+07	.2040E+07	.2091E+07
P=10							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2016E+07	.2022E+07	.2266E+07	.2771E+07
P=20							
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	.5000E+06	.1000E+07	.2000E+07	.2017E+07	.2030E+07	.2517E+07	.3525E+07

TABLE A-12. PERCENT FAILURE AND RELEASE VOLUME BY DESIGN, BENCHMARK TIME, AND CLIMATIC REGIME

(INCOMPATIBLE WASTE SCENARIO)

INCOMPATABLE WASTE SCENARIO
LANDFILL

	Benchmark Time						
	5	10	20	35	50	100	200
DESIGN 1							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1(DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	82.0 .2123E+05	93.8 .7012E+05
P=1(SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	90.4 .2303E+05	96.4 .7201E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	98.7 .2450E+06	99.5 .7323E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.1 .8419E+04	99.4 .4882E+06	99.7 .1462E+07
DESIGN 2							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1(DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	82.0 .2123E+05	93.8 .7012E+05
P=1(SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	90.4 .2303E+05	96.4 .7201E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	98.7 .2450E+06	99.5 .7323E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.1 .8419E+04	99.4 .4882E+06	99.7 .1462E+07
DESIGN 3							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1(DEEP)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	82.0 .2123E+05	93.8 .7012E+05
P=1(SHALLOW)	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	90.4 .2303E+05	96.4 .7201E+05
P=10	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	98.7 .2450E+06	99.5 .7323E+06
P=20	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.1 .8419E+04	99.4 .4882E+06	99.7 .1462E+07
DESIGN 4							
P=0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0	0.0 .0
P=1(DEEP)	0.0 .0	0.0 .0	0.0 .0	100.0 .3238E+02	100.0 .5230E+03	100.0 .2580E+05	100.0 .7599E+05
P=1(SHALLOW)	1.0 .5922E+05	2.8 .6082E+05	15.7 .5422E+05	100.0 .2781E+05	100.0 .2835E+05	100.0 .5372E+05	100.0 .1040E+06
P=10	1.0 .5922E+05	2.8 .6082E+05	15.7 .5422E+05	100.0 .2810E+05	100.0 .3303E+05	100.0 .2848E+06	100.0 .7845E+06

TABLE A-12 (Continued)

P=20	1.0	2.8	15.7	100.0	100.0	100.0	100.0
	.5922E+05	.6082E+05	.5422E+05	.2842E+05	.3823E+05	.5409E+06	.1539E+07
DESIGN 5							
P=0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	.0	.0	.0	.0	.0	.0	.0
P=1(DEEP)	0.0	0.0	0.0	100.0	100.0	100.0	100.0
	.0	.0	.0	.3238E+02	.5230E+03	.2580E+05	.7599E+05
P=1(SHALLOW)	1.0	2.8	15.7	100.0	100.0	100.0	100.0
	.5922E+05	.6082E+05	.5422E+05	.2781E+05	.2835E+05	.5372E+05	.1040E+06
P=10	1.0	2.8	15.7	100.0	100.0	100.0	100.0
	.5922E+05	.6082E+05	.5422E+05	.2810E+05	.3303E+05	.2848E+06	.7845E+06
P=20	1.0	2.8	15.7	100.0	100.0	100.0	100.0
	.5922E+05	.6082E+05	.5422E+05	.2842E+05	.3823E+05	.5409E+06	.1539E+07
SURFACE IMPOUNDMENTS							
DESIGN 1							
P=0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
	.0	.0	.0	.0	.0	.1606E+06	.1606E+06
P=1(DEEP)	0.0	0.0	0.0	0.0	0.0	92.7	97.1
	.0	.0	.0	.0	.0	.2323E+05	.7415E+05
P=1(SHALLOW)	0.0	0.0	0.0	0.1	0.1	96.4	98.4
	.0	.0	.0	.8175E+04	.8180E+04	.2426E+05	.7517E+05
P=10	0.0	0.0	0.0	0.1	0.2	99.4	99.8
	.0	.0	.0	.8217E+04	.5004E+04	.2473E+06	.7518E+06
P=20	0.0	0.0	0.0	0.2	0.2	99.7	100.0
	.0	.0	.0	.4999E+04	.8334E+04	.4929E+06	.1499E+07
DESIGN 2							
P=0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
	.0	.0	.0	.0	.0	.1585E+06	.1585E+06
P=1(DEEP)	0.0	0.0	0.0	0.0	0.0	92.4	97.0
	.0	.0	.0	.0	.0	.2317E+05	.7410E+05
P=1(SHALLOW)	0.0	0.0	0.0	0.1	0.1	96.3	98.4
	.0	.0	.0	.8175E+04	.8180E+04	.2424E+05	.7512E+05
P=10	0.0	0.0	0.0	0.1	0.2	99.4	99.8
	.0	.0	.0	.8217E+04	.5004E+04	.2473E+06	.7518E+06
P=20	0.0	0.0	0.0	0.2	0.2	99.7	100.0
	.0	.0	.0	.4999E+04	.8334E+04	.4927E+06	.1499E+07
DESIGN 3							
P=0	0.0	0.0	0.0	0.1	0.1	0.4	0.4
	.0	.0	.0	.1702E+06	.1702E+06	.1630E+06	.1630E+06
P=1(DEEP)	0.0	0.0	0.0	0.1	0.1	94.8	98.0
	.0	.0	.0	.1702E+06	.1702E+06	.2343E+05	.7471E+05
P=1(SHALLOW)	0.0	0.0	0.0	0.1	0.1	97.3	98.8
	.0	.0	.0	.1869E+06	.1869E+06	.2470E+05	.7554E+05
P=10	0.0	0.0	0.0	0.1	0.2	99.4	99.8
	.0	.0	.0	.1870E+06	.9437E+05	.2476E+06	.7522E+06
P=20	0.0	0.0	0.0	0.2	0.2	99.7	100.0
	.0	.0	.0	.9438E+05	.9772E+05	.4932E+06	.1499E+07

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TABLE A-12 (Continued)

```
DESIGN 4
 P=0
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5407E+05  .6409E+05  .7953E+05  .7953E+05  .7953E+05  .7953E+05  .7953E+05
 P=1(DEEP)
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5407E+05  .6409E+05  .7953E+05  .7958E+05  .8011E+05  .1047E+06  .1555E+06
 P=1(SHALLOW)
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5407E+05  .6409E+05  .7953E+05  .9351E+05  .9466E+05  .1193E+06  .1700E+06
 P=10
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5407E+05  .6409E+05  .7953E+05  .9398E+05  .9988E+05  .3452E+06  .8502E+06
 P=20
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5407E+05  .6409E+05  .7953E+05  .9450E+05  .1057E+06  .5955E+06  .1604E+07
DESIGN 5
 P=0
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5590E+04  .1558E+05  .3223E+05  .3223E+05  .3223E+05  .3223E+05  .3223E+05
 P=1(DEEP)
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5590E+04  .1558E+05  .3223E+05  .3228E+05  .3282E+05  .5745E+05  .1082E+06
 P=1(SHALLOW)
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5590E+04  .1558E+05  .3223E+05  .4684E+05  .4737E+05  .7201E+05  .1227E+06
 P=10
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .5590E+04  .1558E+05  .3223E+05  .4730E+05  .5257E+05  .2979E+06  .8029E+06
 P=20
                      100.0      100.0      100.0      100.0      100.0      100.0      100.0
                     .3590E+04  .1558E+05  .3223E+05  .4782E+05  .5837E+05  .5482E+06  .1557E+07
```

6. Divide the average incremental release volume in (5) by the number of years in the interval between the previous and current benchmark times to obtain the average annual incremental release rate.

7. Use the release rate in (6) for each year in the interval between the previous and current benchmark times.

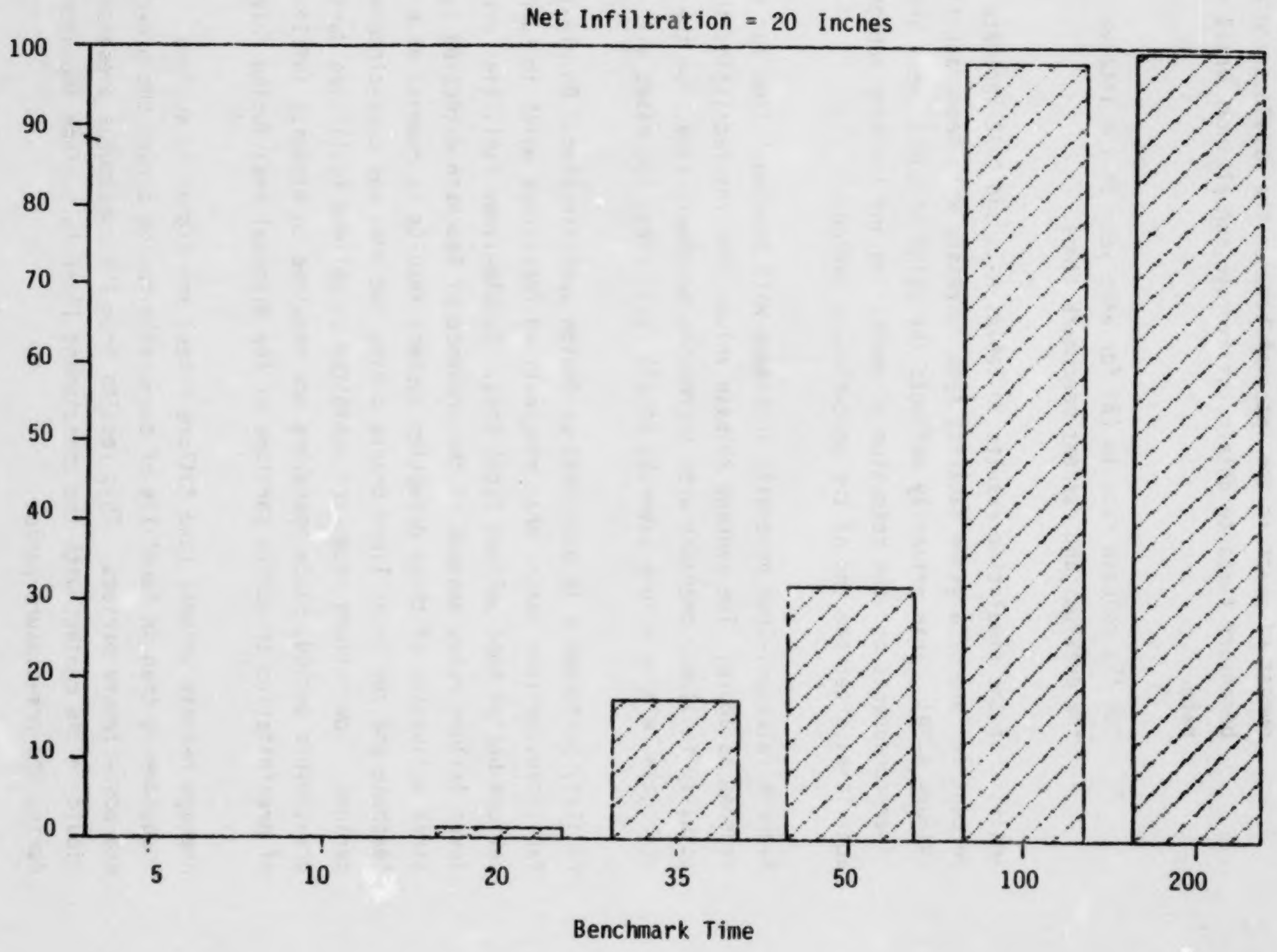
Analysis of the simulation results in Tables A-11 and A-12 indicate that percent failure of a given facility type increases with benchmark time (Figure A-29). This primarily reflects the aging of containment and cover liner components and the cessation of monitoring and leachate management activities after the end of the post-closure period.

Average release volume generally increases with benchmark time for the same reasons as above. The average release volume (for the facilities that actually fail) may decrease with increasing benchmark time, but the aggregate release volume (average of all facilities) increases with time.

Facility performance is dependent on design specification. Double-lined facilities perform better than single-lined facilities which in turn perform better than unlined facilities. Double-lined facilities experience lower failure rates because of the presence of leachate detection systems, since activation of these detection systems results in removal of escaped leachate and repair of liner cracks during the pre- and post-closure periods. Low failure rates are exhibited by unlined facilities during the pre-closure period, since operators are required to minimize infiltration of precipitation to active portions of the disposal area during this time.

Average release volumes (and failure rates) are higher in surface impoundments than in landfills of comparable design during the pre-closure and post-closure periods. This results from the continuous presence of liquid in the contact with the containment liner in surface impoundments during the pre-closure period.

FIGURE A-29. PERCENT FAILURE vs BENCHMARK TIME IN LANDFILL DESIGN IV (2 FT. THICK CLAY LINER)


Net Infiltration = 20 Inches

Comparable clay and synthetic-lined facilities exhibit similar failure rates, all other factors held constant. This is not surprising in view of the assumption that lifetimes for synthetic and clay liners are essentially the same in the failure model. Release volumes are somewhat less in facilities with single clay liners than in synthetic lined facilities (1.4 percent for a 200 year benchmark) because clay liners are assumed to provide permanent storage for some leachate.

Failure rates appear to be influenced by climatic conditions, particularly those in arid and semi arid regions (Figure A-30). The failure release rate for landfill design 4 (at year 200) is 10 to 15% higher for facilities with a net infiltration of twenty inches as compared to those with a net infiltration of one inch. Release rates are also directly related to net infiltration. These observations suggest that cover failures are perhaps the most significant cause of leachate release in the long term.

Several additional generalizations can be made with regard to the failure rate and release rate data:

With respect to climatic regime:

- Failure rates increase slightly with net infiltration.
- Release rates increase with net infiltration.

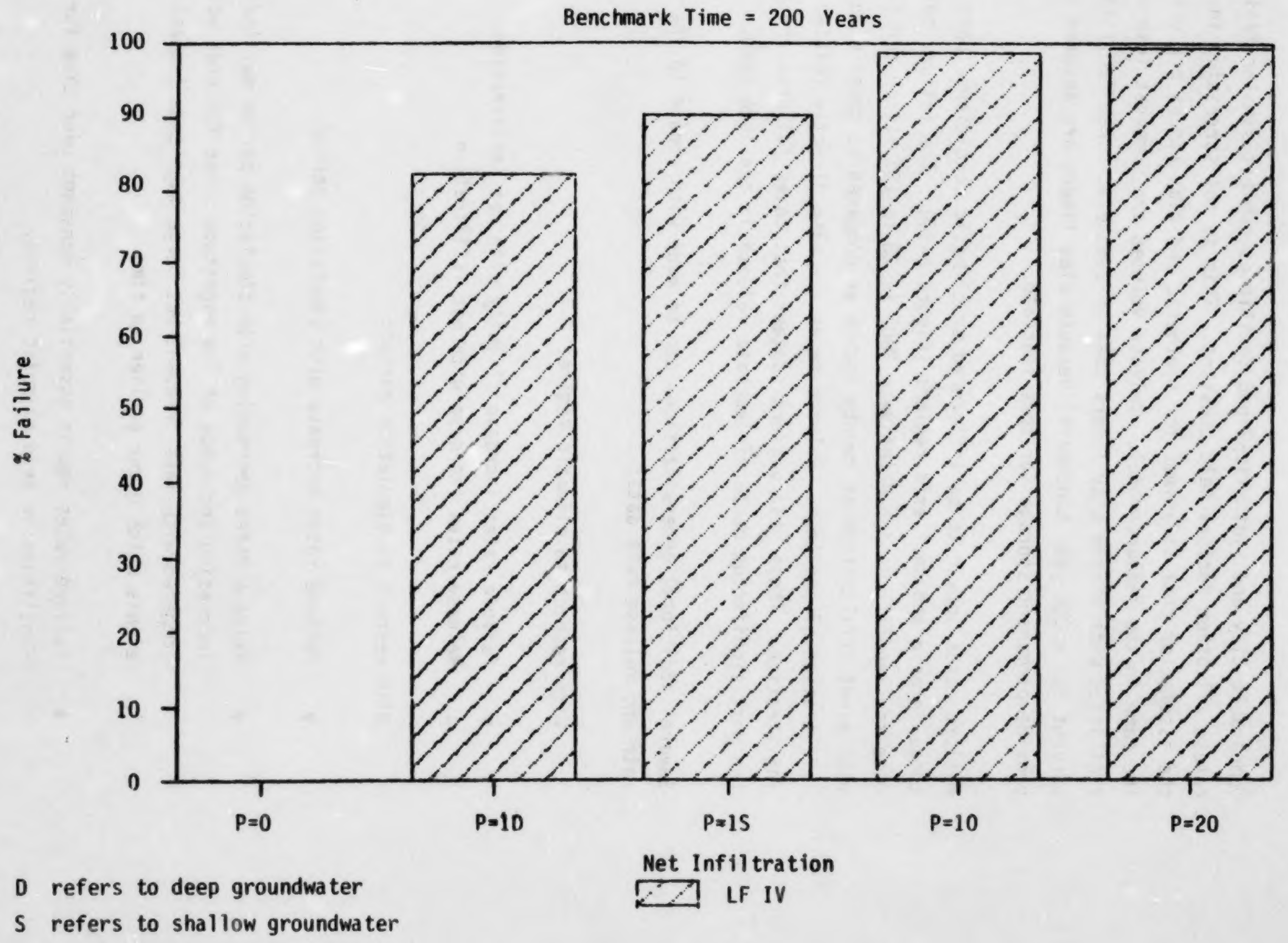
With respect to simulation period:

- Failure rates increase with simulation period.

- Release rates decreasing with simulation period may indicate the increasing incidence of low magnitude cover failures with time, compared with less frequent but large magnitude (catastrophic) events which occur earlier in time.

- Failure rates remain essentially constant over time for facilities in arid climatic regimes.

FIGURE A-30. PERCENT FAILURE vs NET INFILTRATION IN LANDFILL IV (2 FT. THICK CLAY LINER)



D refers to deep groundwater
S refers to shallow groundwater

- Failure rates are very high for a 200 year benchmark, even when liner lifetime is assumed to be 150 years.

With respect to technology:

- Surface impoundments have higher failure rates for facilities within a given climatic regime.

- Surface impoundments generally have higher release rates than landfills for facilities within a given climatic regime.

With respect to design, higher failure rates occur in facilities:

- without drainage collection systems,
- without leachate collection systems,
- with no liners,
- with single rather than double liners,
- without leachate detection systems,

With respect to post-closure care:

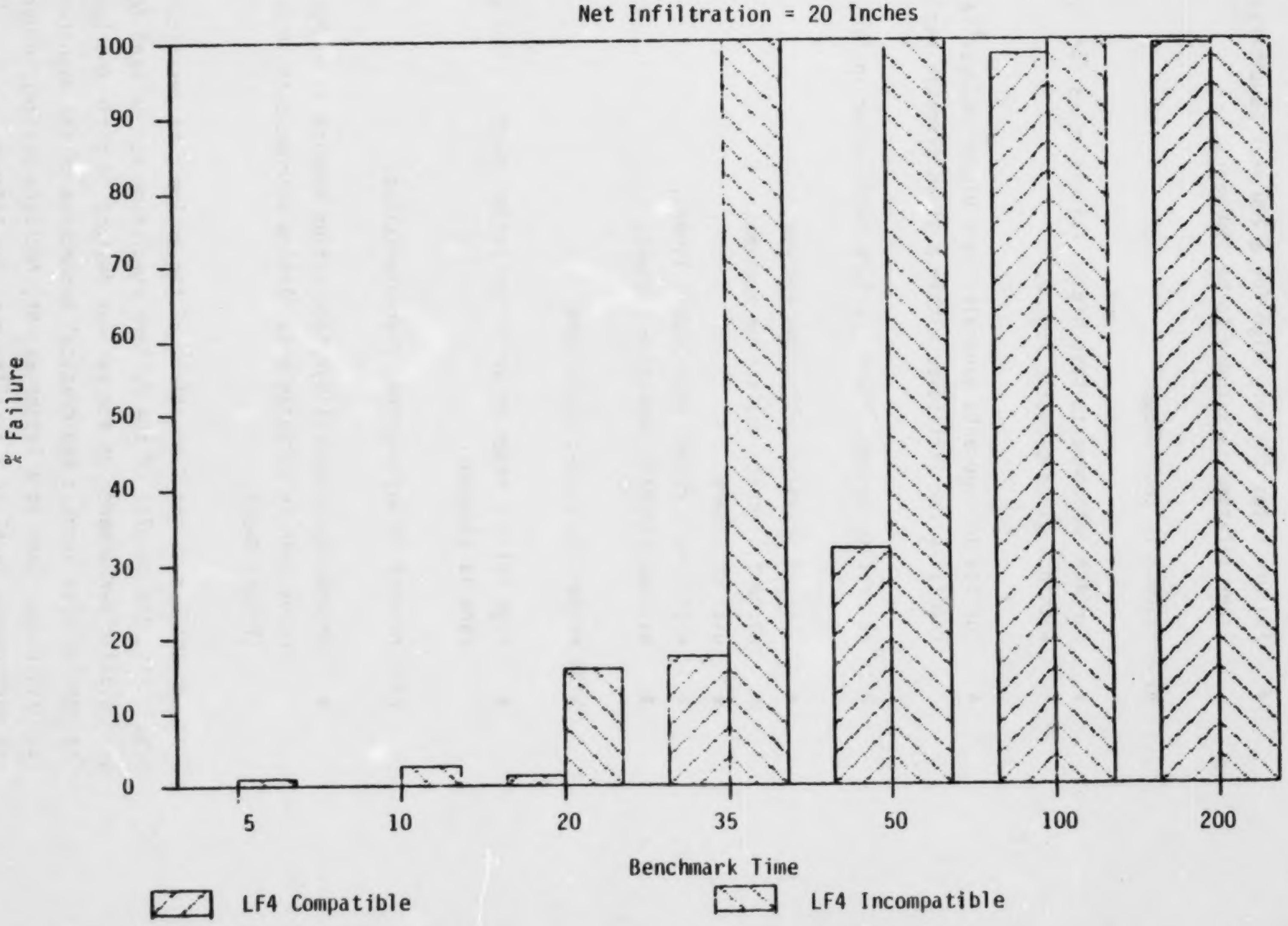
- High failure rates occur in facilities shortly after post-closure care is stopped.

With respect to waste-stream characteristics:

- Incompatible waste-liner interaction results in higher failure rates than in comparable facilities without such interactions (Figure A-31).

Although subject to the limitations of the analysis as described previously, the results of the failure simulation can be used to evaluate the relative performance of the various designs in different locations. The results also suggest the critical importance of the magnitude of the leachate budget (and to a lesser extent, facility design) in determining the performance level of a facility over its lifetime.

FIGURE A-31. PERCENT FAILURE vs BENCHMARK TIME AND WASTE TYPE IN LANDFILL IV (2 FT. THICK CLAY LINER)



Net Infiltration = 20 Inches

5. FUTURE EFFORTS

At its current level of development, the failure model provides a useful technique for evaluating relative system performance of a variety of design configurations. However, considerable work remains to be completed before the failure model can be applied to specific facility sites in order to obtain accurate estimates of expected failure rate and release volume. Several aspects of the model, and the data upon which it is based, can be refined to arrive at more realistic estimates of land disposal facility performance. These areas include:

- Expanding the data base and refining the probability distribution parameters describing the occurrence of individual events.
- Improving the hydrologic input budgets.
- Modifying the model structure to reflect more realistic design, operating, and maintenance aspects of disposal facilities.
- Modifying the output format of the model to obtain more precise estimates of leachate release rates.

5.1 Refine Probability Parameters

The most critical of these areas would involve collection of data regarding the aging of synthetic and clay liners. The model results are particularly sensitive to the time period selected for liner aging. A program of carefully conducted field studies at existing facilities or bench-scale models would be helpful in evaluating the relative performance of liner types in different waste stream environments and over different time periods. EPA is conducting such studies through the Research and Development Branch in Cincinnati. Liner aging also has a significant impact upon the efficiency of leachate collection systems. Again field studies, or perhaps electric analogue analysis or numerical models of partially functioning leachate collection systems are necessary. Numerical studies using an analytic flow model, are currently underway to refine the estimates of collection system efficiencies.

Information from the RIA data base can be evaluated to provide more accurate estimates of some of the probabilities of the events comprising the failure scenarios; for example in determining the proportion of facilities subject to certain location-specific events, such as periodic flooding or seismic activity. Alternatively, it has also been suggested to treat the location-specific events strictly as house gates, that is to consider all facilities in a given set of runs to lie either within or outside areas subject to a given geological hazard. This would be done to compare the performance of facilities in different locational settings.

Finally, comments from the peer-review will be evaluated to determine if distribution types and parameters should be modified for specific events. An example would include replacing the triangular distribution for liner aging with a Weibull or normal probability distribution.

5.2 Hydrologic Inputs

Facility performance is highly dependent upon the leachate budget in the model. Attempts should therefore be made to bracket as tightly as possible the range of volumes of the contributing hydrologic volumes to the model. This would entail a more realistic treatment of flow through cracks in active impoundments, incorporating slow diffusional releases through landfill liners, accounting for storage of leachate in waste fill materials that have not attained field capacity, improving estimates of release from run-on and flooding events, revising the hydrologic input volumes to a unit area basis to permit scaling of results to a variety of facility capacities, and changing the method used to determine infiltration volumes to more adequately reflect long-term and seasonal variations in precipitation and evaporation.

5.3 Model Structure

Several changes in the structure of the model can be made to more realistically reflect design, operating, and maintenance procedures at actual facilities. Such efforts would include the assumption of a trapezoidal geometry (non-vertical side slopes), the simulation of multiple-occurrence events (e.g., floods and earthquakes), explicit provisions for detection and repair of major components, allowance for partial or complete removal of constituents either collected by leachate collection systems in landfills or removed through discharge pipes in surface impoundments, and incorporation of "staged" aging of components to reflect incremental disposal methods.

5.4 Output Format

Experimentation with the model should be conducted to determine the optimum frequency of benchmark sampling periods in order to improve the accuracy of the release and failure rate estimates, while minimizing computational costs. Implementation of these improvements should result in a more flexible, accessible, and powerful model and one that will enable the agency to make more effective evaluations of the risks and costs of a wide range of alternative design and operating standards.

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APPENDIX B

SUBSURFACE TRANSPORT SUBMODEL

1. INTRODUCTION

Appendix B describes the methodologies, results, and critical assumptions and limitations of subsurface chemical mass transport modeling conducted in support of the exposure modeling task of this project. Geraghty & Miller (G&M) developed a conceptual flow model, then selected the necessary mathematical models for transport through the unsaturated and saturated zones to points of exposure downgradient from a hypothetical facility. Model input is considered to be representative of subsurface environments at 70 site-visit facilities.

G&M's scope of work involved meeting three major objectives, summarized as follows:

- Identify the range of hydrogeologic conditions at all site-visit facilities under consideration
- Select appropriate conceptual and mathematical models for predicting mass transport with time in the subsurface
- Run the models for scenarios representing the site-visit facilities.

The values assigned to the various model parameters were derived from a combination of site-specific information and generic hydrogeologic characteristics. The latter were based on a survey of representative hydrogeologic studies performed in groundwater regions as defined and mapped by the U.S. Geological Survey (USGS).

The transport of contaminants through the unsaturated zone was simulated with a simple wetting-front model that estimates the time delay for transport from the release point at the facility to the top of the saturated zone. The mass loading to the saturated zone was equated to mass releases from the facility. Attenuation of contaminants by biodegradation in the unsaturated zone was assumed to be negligible in G&M's analysis. First order decay of contaminant concentrations was introduced for some constituents in the exposure modeling portion of the project (see Appendix G).

The Random-Walk particle-tracking model of Prickett, and others (1981) was selected for simulating mass transport in the saturated zone. Aquifer geometry and groundwater velocities were selected on the basis of data collected in the literature survey. Mass loading from the facility was standardized to permit application to other, specific site-visit facilities. Output is in the form of tables of contaminant concentration versus time in water produced by hypothetical wells, and mass loading versus time in water discharged to hypothetical surface water bodies. Tables of output are included in a separately bound document available from EPA entitled "Random-Walk Model Code and Output for the Liner-Location Project."

There are five critical modeling assumptions that tend to make the G&M-computed concentrations and mass loadings conservatively large by at least one order-of-magnitude. These are:

- Locating the exposure points directly downgradient of the hypothetical facility.

- Maintaining a constant aquifer thickness which sets a limit on plume thickness and contaminant concentrations.

- Use of small dispersivities and ignoring transverse dispersion in a third dimension.

- Not considering the dilution of contaminants that usually takes place inside water wells that produce from multiple zones.

- Neglecting any biodegradation in the unsaturated zone.

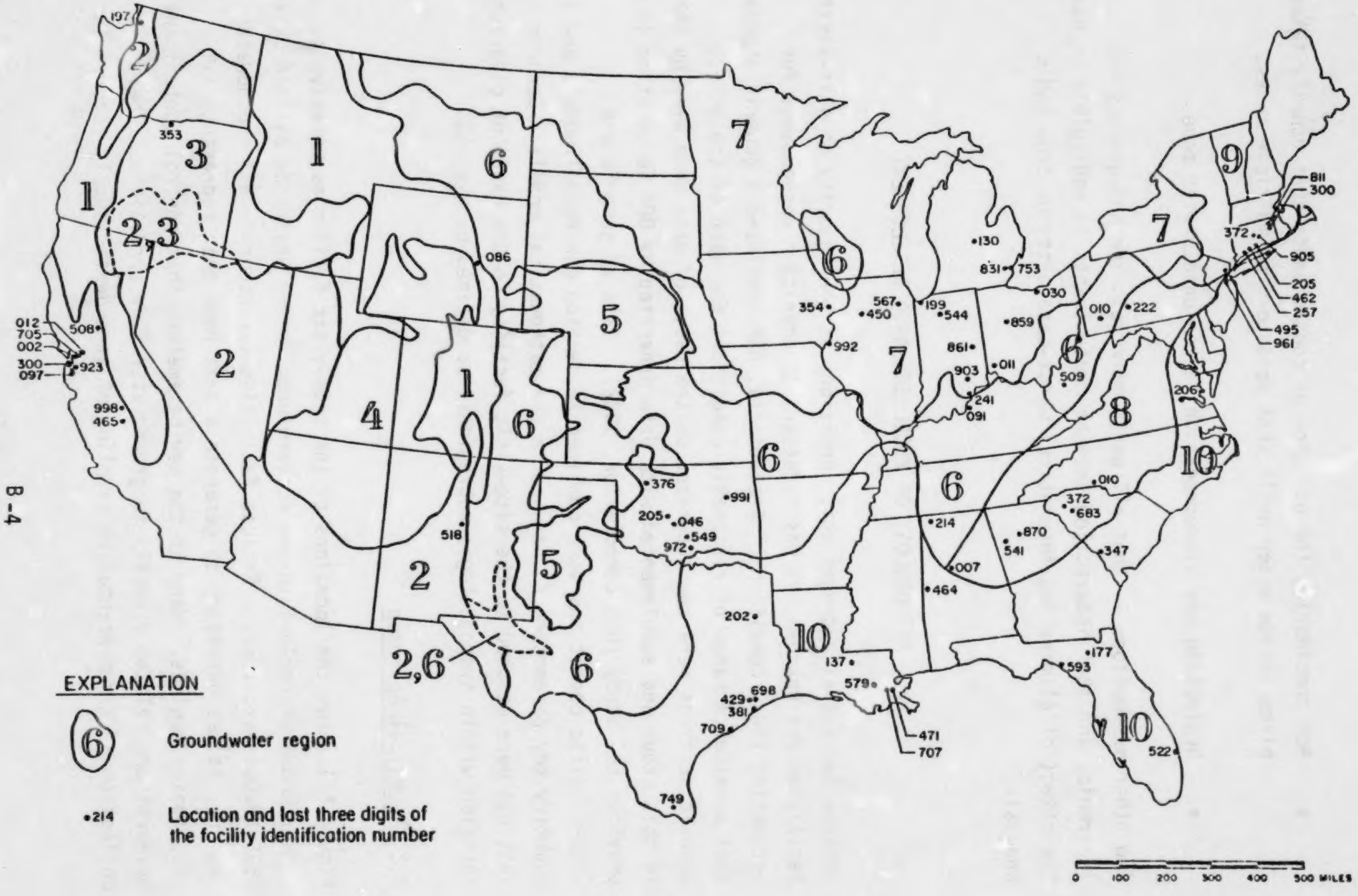
Two other assumptions -- that all earth materials are homogeneous and isotropic, and that interaction between contaminants is negligible -- have the effect of eliminating theoretical worst-case settings from G&M's analysis.

2. METHODOLOGY OF MODEL SCENARIO DEVELOPMENT

Because the actual hydrogeologic conditions at the majority of site-visit facilities are unknown, it was necessary to develop a methodology for estimating these conditions. Accordingly, G&M developed a generic approach that provides a range of reasonable conditions for each of the sites. Generic settings were characterized on the basis of data generated by G&M in this study and supplemented with data generated by GCA Corporation in a previous EPA study (GCA Corporation, 1982). Sets of generic and site-specific conditions were combined to develop conceptual models and to quantify key parameters to be used in the mathematical models. Generic settings were matched to the site-visit facility on the basis of geographic location within hydrogeologic subregions, as defined by the USGS.

2.1 Technical Approach

Figure B-1 shows the locations of the site-visit facilities relative to the ten groundwater regions in the conterminous United States as defined by the USGS (McGuiness, 1963). Because facilities can occur in all groundwater regions, it was necessary to generate a data base that represents all groundwater regions. Many of the key parameters that control contaminant movement are related directly to groundwater flow conditions. The collection of a representative sampling of groundwater supply reports in


EXPLANATION
6 Groundwater region
•214 Location and last three digits of the facility identification number
0 100 200 300 400 500 MILES
1
2
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2,3
1
6
7
9
7
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5
2
2,6
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10
197
353
086
012
705
002
300
097
508
923
998
465
518
376
205
046
549
972
991
202
429
698
381
709
749
354
992
567
450
199
544
861
903
241
091
011
130
831
753
030
859
010
222
509
206
811
300
372
905
205
462
257
495
961
010
372
683
870
541
347
214
007
464
137
579
471
707
177
593
522

Figure B-1. Locations of Site-Visit Facilities with Respect to the Lower 48 States and 10 USGS Groundwater Regions (after McGuiness, 1963).

all regions was judged adequate to provide a suitable data base for this project.

Each USGS groundwater region is subdivided into smaller subregions on the basis of the presence or absence of an underlying aquifer. The reader is referred to a map of the United States in McGuiness (1963) that shows the locations of 32 subregions. Aquifers in these subregions are defined as materials that will provide water with less than 2,000 parts per million total dissolved solids at a rate of at least 50 gallons per minute to operating water wells. This definition for aquifers was adopted for this project and served as a basis for dividing all materials into two classes - aquifers and non-aquifers.

Table B-1 shows a list of 11 USGS groundwater regions and 32 corresponding hydrogeologic subregions. The eleventh region, which includes alluvial deposits associated with major perennial streams, was added to the 10 regions of McGuiness (1963) based on a more recent USGS classification proposed by Heath (1982). The eleventh region is discontinuous and partially overlies all the other regions. It is not shown in Figures B-1 and B-2. The reader is referred to McGuiness (1963) and Heath (1982) for better definition of the distribution and location of this region.

An attempt was made to select hydrogeologic studies in each of the 32 subregions. Groundwater modeling studies were given special preference because they are often based on large data bases, provide more confidence since outputs are calibrated against field data, and offer a more convenient format for providing groundwater flow information.

Approximately 200 reports were considered in the literature search. Of this number, 67 were judged to be suitable for the purpose of this project. G&M assumed that this population of site studies was adequate to allow definitive generalizations to be made in developing the generic flow fields. Data collected from these reports are summarized in Table B-2 and locations of the study areas are shown in Figure B-2. The reader will note that data in Table B-2 are clustered into three major groups:

TABLE B-1

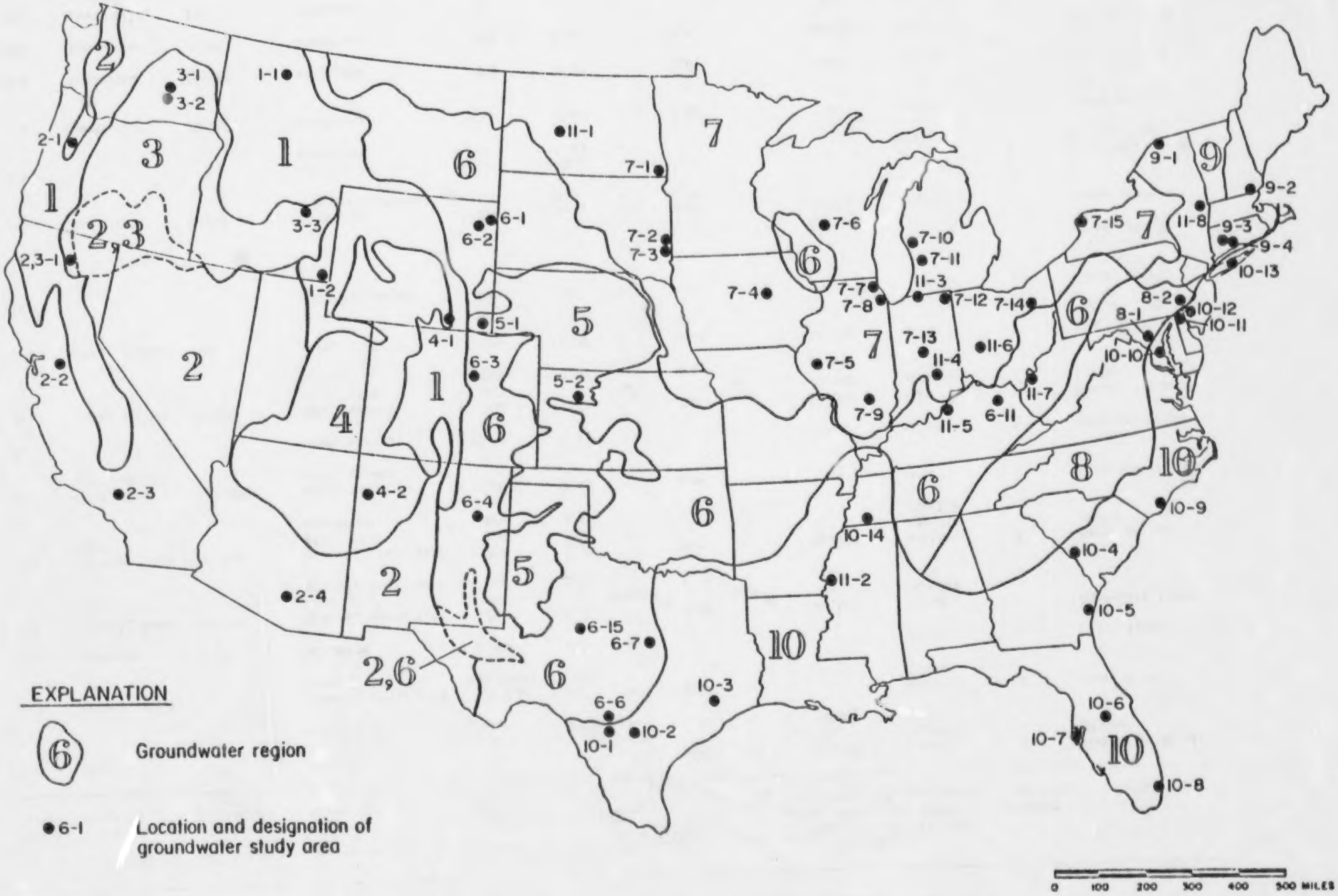
BRIEF DESCRIPTIONS OF GENERIC HYDROGEOLOGIC SUBREGIONS

USGS Region Number	Generic Subregion Number	General Hydrogeology	General Climate
1	1A	Alluvial basin fill aquifer[a]	Temperate[b]
	1B	Undifferentiated bedrock	Alpine; humid to temperate
	1C	Undifferentiated bedrock aquifer	Temperate
2	2A*	Alluvial basin fill aquifer	Humid
	2A	Alluvial basin fill aquifer	Temperate to arid
	2B	Undifferentiated bedrock	Semi-arid to arid
3	3A	Alluvial aquifer over basalt aquifer	Semi-arid to arid
	3B	Basalt aquifers	Semi-arid to arid
	3C	Undifferentiated bedrock	Temperate to semi-arid
4	4A	Alluvial fill aquifer	Semi-arid
	4B	Undifferentiated bedrock	Semi-arid
	4C	Carbonate aquifers	Semi-arid
5	5A	Poor consolidated sandstone aquifer	Temperate to semi-arid
	5B	Undifferentiated bedrock	Temperate
6	6A	Alluvial aquifer over bedrock	Semi-arid
	6B	Undifferentiated bedrock	Temperate to semi-arid
	6C	Carbonate aquifer	Temperate to semi-arid
	6D	Sandstone aquifer	Temperate to semi-arid
7	7A	Glacial over bedrock aquifer	Temperate
	7B	Glacial drift over undifferentiated bedrock	Temperate to semi-arid
	7C	Glacial drift over limestone aquifer	Temperate
	7D	Glacial drift over sandstone aquifer	Temperate
8	8A	Saprolite aquifer over crystalline bedrock	Temperate to humid
	8B	Residuum over limestone/sandstone aquifer	Temperate to humid
	8C	Crystalline bedrock	Temperate to humid
9	9A	Undifferentiated sand, gravel, sandstone aquifer	Temperate
	9B	Glacial drift over bedrock	Temperate
10	10A	Undifferentiated sand, gravel, sandstone aquifer	Temperate to arid
	10B	Undifferentiated silts, clay, shale bedrock	Temperate
	10C	Carbonate aquifer	Temperate
	10D	Multiple carbonate aquifer	Temperate
11	11	Fluvial/glacial sand - gravel aquifer near perennial streams	Temperate to semi-arid

---

[a] Aquifer is defined as being capable of yielding water to continuously discharging well operating at 50 gal/min.

[b] Arid = $\leq$10 in/yr; Semi-arid=10-20 in/yr; Temperate = 20-50 in/yr; Humid $\geq$ 50 in/yr


EXPLANATION
Groundwater region
Location and designation of groundwater study area
6-1
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3-3
4-1
4-2
5-1
5-2
6-1
6-2
6-3
6-4
6-6
6-7
6-11
6-15
7-1
7-2
7-3
7-4
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7-15
8-1
8-2
9-1
9-2
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9-4
10-1
10-2
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10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
11-1
11-2
11-3
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200
300
400
500 MILES

Figure B-2. Locations of Literature Survey Study Areas in Relation to the Lower 48 States and 10 USGS Groundwater Regions (after McGuiness, 1963).

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TABLE B-2
HYDROGEOLOGIC DATA COLLECTED FROM LITERATURE SURVEY

	Unsaturated Zone		Saturated Zone						Flow System			
Study Area	Earth Material	Layer Thickness (ft)	Earth Material	Layer Thickness (ft)	Flow Velocity (ft/day) Min V_h	Min V_a	Max V_h	Max V_a	Distance From Rech. to Dischg. Boundaries[b] (ft)	Primary Mode of Discharge	Generic Setting	Source
1-1	gravel	-[c]	gravel	25	25	-	110	-	21,000	river	1	Konizeski et al.
			silt, clay	300	-	0.006	-	-		aquifer		(1968)
			sand, gravel	>400	0.01	-	0.04	-	40,000	river		
1-2	gravel, sand	-	gravel, sand, silt	0-3000	2.8	-	6.3	-	-	river	5	Dion (1969)
			basalt	400-1000	65	-	-	-	-	river		
2-1	alluvium	10-20	alluvium	30-40	4.5	-	-	-	-	river	1	Price (1962)
2-2	gravel, sand	50-100	gravel, sand, silt	150	0.35	-	2.10	-	42,000	river	1	Londquist (1981)
			clay	60	-	3.6×10^{-6}	-	6×10^{-6}	-	aquifer		
			gravel, sand, silt	600	0.70	-	2.10	-	-			
2-3	gravel, sand silt	50-100	gravel, sand, silt	300	1.7	-	5.0	-	21,000	wells	1	Hardt et. al
			clay, silt	200	-	2	-	6	-	aquifer		(1980)
			sandstone	>400	0.9	-	1.8	-	-	aquifer		
2-4	clay, silt sand, gravel	100-250	clay, silt sand, gravel	>200	0.63	-	1.6	-	27,000	well	1	Anderson (1972)
2,3-1	-	-	sand, gravel	30-60	0.21	-	-	-	-	river	1	Bertoldi (1973)
3-1	sand, gravel	20-200	sand, gravel;	200	67	-	220	-	32,000	lake	7	Tanaka et al.
			clay, silt	100	-	4[d]	-	10[d]	32,000	aquifer		(1974)
			basalt	>100	0.08	-	0.21	-	32,000	aquifer		
3-2	sand, gravel	200	silt, sand	>1200	0.38	-	0.64	-	53,000	wells	1	Newcomb et al. (1972)
3-3	-	-	sediment, basalt	5000	5	-	25	-	-	-	1	Barraclough, et al. (1976) Robertson, et al. (1974)
4-1	sandstone	0-300	sandstone	0-700	0.11	-	0.22	-	21,000	spring	1	Lundy (1978)
			faulted sandstone	>100	5.6	-	12.0	-	-	-		
4-2	-	-	sandy clay	0-135	0.025	-	-	-	-	wells	6	Raymondi,
			sandstone	70	0.43	-	-	-	-	wells		et al. (1983)
5-1	sandstone	20-80	sandstone	>300	0.09	-	0.60	-	-	wells	1	Lowry et al. (1967)
5-2	sandstone	50-100	sandstone	150	0.27	-	3.0	-	21,000	stream	1	Hodson (1965)
6-1	limestone	0-500	limestone	550	0.04	-	0.4	-	53,000	aquifer	1	Konikow (1976)
6-2	sand, silt, gravel	10	sandstone	20	-	-	-	-	3,000	stream	1	Davis (1975)
	sandstone	20-50	coal	70	0.61	-	3.0	-	-			
6-3	sand, silt, gravel	-	sand, silt, gravel	15	0.80	-	5.3	-	6,000	river	1	Konikow (1976)

TABLE B-2 (Cont'd)
HYDROGEOLOGIC DATA COLLECTED FROM LITERATURE SURVEY

Study Area	Unsaturated Zone		Saturated Zone						Flow System		Generic Settting	Source
	Earth Material	Layer Thickness (ft)	Earth Material	Layer Thickness (ft)	Flow Velocity Min V_h (ft/day)	Flow Velocity Min V_v^a (ft/day)	Flow Velocity Max V_h (ft/day)	Flow Velocity Max V_v (ft/day)	Distance From Rech. to Dischg. Boundaries[b] (ft)	Primary Mode of Discharge		
6-4	sandstone	50-200	sandstone	300	0.20	–	0.40	–	16,000	well	1	Trauger et al. (1964)
6-5	–	6-10	limestone	50	0.49	–	–	–	–	spring	1	Tuck et al. (1971)
6-6	fractured limestone	0-200 –	fractured limestone	600	0.13	–	0.24	–	–	spring	1	Klempt et al. (1979)
6-7	limestone	–	sandstone shale, limestone sandstone	100 50 100	0.04 – 0.06	– $2x10^{-5d}$ –	0.16 – 0.26	– $2x10^{-4d}$ –	–	aquifer aquifer aquifer	7	Hall et al. (1975)
6-8	–	–	karstic limestone	–	26	–	–	–	5,000	stream	1	Harvey et al. (1968)
6-9	–	–	karstic dolomite	–	1.9	–	2.6	–	–	–	1	Skelton et al. (1979)
6-10	karstic limestone	–	karstic limestone	>1,000	24	–	180	–	–	spring	1	Harvey (1980)
6-11	shale	–	shale, siltstone sandstone shale	40 40 >300	– 0.03 –	0.002^d – 0.008^d	– 0.26 –	0.003^d – 0.01^d	– – –	aquifer spring aquifer	3	Zehner (1983)
7-1	sand, gravel	10	sand, gravel granite	150 –	0.02 –	– –	0.05 –	– –	53,000 –	spring –	1	Baker et al. (1967)
7-2	–	–	sand, gravel, silt	–	1	–	3	–	–	–	1	Otton (1972)
7-3	sand, gravel	–	sand, gravel	90	0.64	–	1.3	–	10,000	river	1	Rothrock et al. (1947)
7-4	till, sand	8	till, sand shale limestone	>1000 200 25-260	– – 0.025	– – –	– – 0.58	– – –	– – –	aquifer –	3	Kent et al. (1972)
7-5	–	–	sand, gravel	90	3.4	–	–	–	16,000	river	1	Kaymick et al. (1981)
7-6	–	–	sand	75-130	1.5	–	1	–	130,000	river	1	Rothschild et al. (1982)
7-7	sand, gravel	–	sand, gravel dolomite	50 200	– 0.21	– –	– 0.43	– –	– –	– wells	1	Zeizel et al.
7-8	–	–	sand, gravel		0.04	–	0.27	–	–	–	1	Otton (1972)
7-9	silt	–	clay, silt	50	0.15	–	1.8	–	600	stream	1	Gibb (1978)
7-10	–	–	sand, gravel	–	1	–	–	–	–	–	1	Otton (1972)

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TABLE B-2 (Cont'd)
HYDROGEOLOGIC DATA COLLECTED FROM LITERATURE SURVEY

	Unsaturated Zone		Saturated Zone		Flow Velocity (ft/day) Min		Flow Velocity (ft/day) Max		Flow System			
Study Area	Earth Material	Layer Thickness (ft)	Earth Material	Layer Thickness (ft)	V_h	V_v^a	V_h	V_v^a	Distance From Rech. to Dischg. Boundaries[b] (ft)	Primary Mode of Discharge	Generic Setting	Source
7-11	silt, clay		sand, gravel	40	1.3	-	4.8	-	-	river	1	Planert (1980)
			silt, clay	60	1	$8x10^{-5}$	-	$6x10^{-4}$	-	aquifer		
			sand, gravel	50	1.4	-	4.8	-	-	-		
			limestone	100	-	-	-	-	-	-		
7-12	sand, gravel	10	sand, gravel	30	0.01	-	0.10	-	-	creek	2	Pettijohn (1977)
			silt, clay	100	-	0.001	-	0.002	-	aquifer		
			sand, gravel	20	0.8	-	1.6	-	-	underflow		
7-13	sand, gravel, silt	10	sandstone	74	18	-	51	-	16,000	river	1	Matisoff et al. (1982)
			clay till	20-217	-	-	-	-	-			
7-14	till	10-20	till	30	0.0055	-	-	-	5,200	river	3	Maslia et al. (1982)
			dolomite	15	0.055	-	-	-	5,200	river		
			dolomite	60	0.03	-	-	-	5,200	river		
			shale	>50	$1x10^{-5}$	-	-	-	4,200	river		
8-1	saprolite	3-17	saprolite	0-50	0.023	-	0.043	-	-	streams	2	Maryland DLP (1981)
8-2	gneiss (weathered)	-	gneiss (weathered)	100	0.56	-	3.1	-	5,000	stream	1	McGreevy and Sloto (1980)
9-1	silt, clay	10	silt, clay	100	0.002	-	0.01	-	10,500	river	1	Trainer et al. (1962)
			dolomite	>100	0.17	-	0.69	-	10,500			
9-2	sand, gravel		sand, gravel	35	1.9	-	6.2	-	-	creek	1	Gushue et al. (1981)
9-3	sand, gravel	10	sand, silt, clay	80	2.4	-	14	-	3,200	river	1	Harni (1978)
			crystalline rock	>500	-	-	-	-	-	aquifer		
9-4	sand, silt, clay	-	sand, silt, clay	200	0.36	-	3.0	-	2,000	river	1	LaSala (1968)
			basalt	>500	-	-	-	-	-	-		
10-1	-	-	sand	1000	0.006	-	0.29	-	-	-	1	Pearson et al. (1967)
10-2	sand	150	sand	>400	0.28	-	0.47	-	-	stream	1	Alexander et al. (1966)
10-3	sand	-	sand, gravel	>1000	0.05	-	0.2	-	-	wells	1	Wool et al. (1965)
10-4	clay, sand	10-30	clay, sand	20	0.042	-	8.4	-	3,000	springs	5	Cahill (1982)
			sand	100	0.02	-	4.3	-	3,000	springs		
			sand	150	0.02	-	0.2	-	3,000	creek		
			silty clay	75	-	-	-	-	-	-		
10-5	-	-	limestone	100	0.58	-	-	-	52,000	creek	1	McCollum et al. (1964)
10-6	-	-	limestone	>1000	0.018	-	0.018	-	-	ocean	1	Hanshaw et al. (1965)
10-7	-	-	sand, clay	23	0.0035	-	0.008	-	-		2	Hutchinson et al. (1978)
10-8	-	-	sandstone, limestone	100	1.8	-	3.5	-	-	well	1	Kohout (1960)

TABLE B-2 (Cont'd)
HYDROGEOLOGIC DATA COLLECTED FROM LITERATURE SURVEY

Study Area	Unsaturated Zone		Saturated Zone						Flow System			
					Flow Velocity (ft/day)							
					Min		Max					
	Earth Material	Layer Thickness (ft)	Earth Material	Layer Thickness (ft)	V_h	V_v[a]	V_h	V_v[a]	Distance From Rech. to Dischg. Boundaries[b] (ft)	Primary Mode of Discharge	Generic Settting	Source
10-9	sand	–	sand	100	0.53	–	1.1	–	–	wells	1	North Carolina D.N.R. (1978)
			clay	30	–	–	–	–	–			
10-10	sand, gravel	30	sand, gravel	200	0.24	–	0.64	–		wells	7	Mack (1962)
			clay	200	–	1×10^{-5}	–	6×10^{-4}	–	aquifer		
			sand, gravel	100	0.10	–	0.26	–	–	aquifer		
			crystalline rock	>100	–	–	–	–	–			
10-11	–	–	sandstone	80	0.84	–	–	–	–		1	Baedecker et al. (1979) DeWalle et al. (1981)
10-12	sand, gravel	10-20	sand, gravel	200	0.03	–	0.10	–	42,000	well	1	Luzier (1980)
			schist	>100								
10-13	sand, gravel	10-100	sand, gravel	90	0.16	–	0.72	–	53,000	stream	1	Getzen (1972)
			clay	20	–	1×10^{-4}	–	5×10^{-4}	–	aquifer		
			sand, gravel	200	0.04	–	0.19	–	–	well		
10-14	sand, silt, clay	90	sand	10	1.3	–	2.1	–	–	stream	1	Sprinkle (1978)
			silty clay	100	–	–	–	–	–	–		
11-1	sand, gravel	–	sand, gravel	150	0.64	–	1.3	–	10,000	river	1	Croft (1973)
			sandstone	>200	–	–	–	–	–	–		
11-2	sand, gravel	–	sand, gravel	100	0.32	–	0.64	–	–	–	1	Dalsin (1978)
11-3	sand, gravel	–	sand, gravel	30	0.22	–	0.45	–	2,000	river	8	Marie (1975)
			fine sand	100	–	0.04[d]	–	1.2[d]	100	aquifer		
			sand, gravel	30	1.3	–	2.2	–	–	river		
			shale	>50	–	–	–	–	–	–		
11-4	sand, gravel	–	sand, gravel	100	0.45	–	3.0	–	13,000	river	1	Planert et al. (1979)
			limestone	–	–	–	–	–	–	–		
11-5	–	–	sand, gravel	–	5	–	–	–	–	river	1	Grubb (1970)
11-6	sand, gravel	–	sand, gravel	100	0.45	–	3.0	–	5,000	well	1	Walton et al. (1960)
			shale	>200	–	–	–	–	–			
11-7	sand, silt, clay	–	sand, silt, clay	75	27	–	55	–	15,000	river	1	Wilmoth (1966)
11-8	sand, gravel	–	sand, gravel	200	27	–	80	–	–	wells	1	Winslow et al.
			shale, schist	>500	–	–	–	–	–	–		

---

[a] Vertical groundwater flow is upward unless otherwise indicated

[b] Maximum horizontal distance from recharge to discharge groundwater divides

[c] A dash indicates that information was not reported

[d] Downward groundwater flow

- Unsaturated zone
- Saturated zone
- Groundwater flow system

Relevant information for modeling purposes includes earth material type, thickness of each layer or zone, groundwater velocity, the dimensions of the entire regional groundwater flow system, and the primary mode of discharge from the flow system. Generic settings listed in Table B-2 are discussed in a later section and are described in Figure B-4.

The majority of the reports selected by G&M deals with aquifers that, to some degree, have been developed for water supply. Therefore, groundwater velocity data in Table B-2 represents varying degrees of aquifer pumping stresses. For this reason, the velocities assigned to the model scenarios generally represent stressed conditions.

2.2 Scenario Characterization

A transport model scenario is defined on the basis of a physical system that is characterized by flow-oriented and contaminant transport-oriented components. The data generated from the literature survey were used to conceptualize and quantify generic groundwater flow conditions. These flow characteristics were supplemented with selected transport characteristics as quantified with data from the general groundwater literature and by work performed by other EPA contractors on the project team.

2.2.1 Flow Characteristics

The subsurface flow system in the immediate proximity of a site was conceptualized as occupying a two-dimensional vertical plane passing through the center of the facility to a depth that represents the base of shallow groundwater circulation beneath the site. The conceptual flow system is composed of an unsaturated zone overlying a saturated flow field.

Figure B-3 illustrates a conceptual flow system under a hypothetical site-visit facility. The facility is located at the right-hand end of the flow system and terminates in the unsaturated zone above the water table. Each layer has a rectangular geometry and simplified boundary conditions. Unsaturated flow is also simplified to one-dimensional flow in the vertical direction. Saturated flow is conceptualized as two-dimensional with water entering the right-hand boundary and leaving the left-hand boundary at the same, constant rate of flow. The lower boundary on the system is the assumed depth limit on plume growth. All earth materials in the model are placed into one of two major classes -- aquifer and non-aquifer, each with a range of possible hydraulic parameters.

The earth material type in the unsaturated zone is assumed to be equivalent to the material type in the uppermost layer of the saturated zone. Typical values for the hydraulic parameters of the unsaturated zone are listed in Table B-3. These values are based on published data including a literature survey for this project and G&M's professional judgment. Thicknesses of the unsaturated zone are reported in Table B-4.

The generic settings in the saturated zone were developed according to the following methodology:

- Identify generic hydrogeologic settings based on literature review

- Characterize each of 32 hydrogeologic subregions according to generic settings

- Identify the hydrogeologic subregion for each site-visit facility

- Develop corresponding generic flow fields for each subregion/facility.

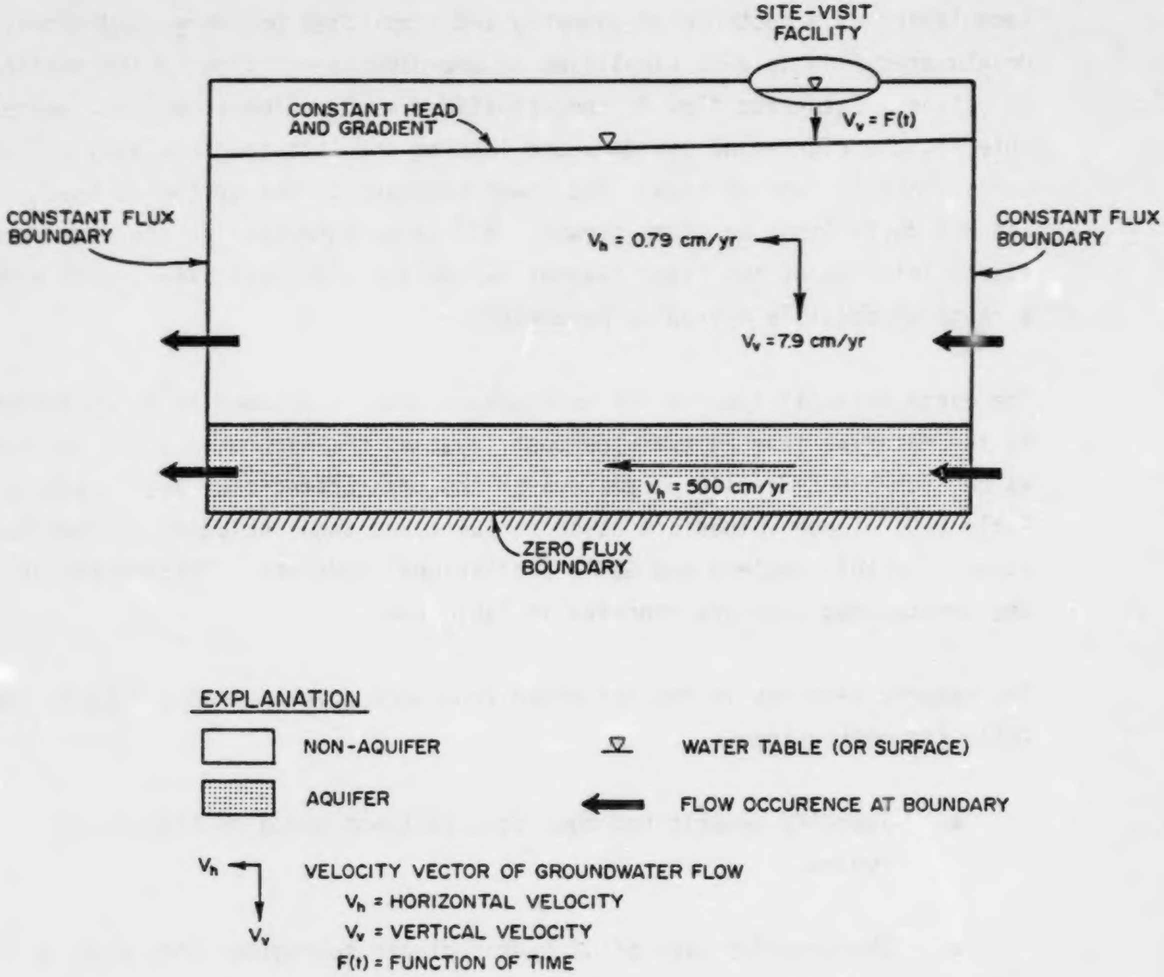
SITE-VISIT FACILITY
CONSTANT HEAD AND GRADIENT
$V_v = F(t)$
CONSTANT FLUX BOUNDARY
CONSTANT FLUX BOUNDARY
$V_h = 0.79$ cm/yr
$V_v = 7.9$ cm/yr
$V_h = 500$ cm/yr
ZERO FLUX BOUNDARY
EXPLANATION
NON-AQUIFER
AQUIFER
WATER TABLE (OR SURFACE)
FLOW OCCURENCE AT BOUNDARY
V_h
V_v
VELOCITY VECTOR OF GROUNDWATER FLOW
V_h = HORIZONTAL VELOCITY
V_v = VERTICAL VELOCITY
F(t) = FUNCTION OF TIME

Figure B-3. Example of a Conceptual Subsurface Flow System.

TABLE B-3

RANGE OF MODEL PARAMETER VALUES FOR UNSATURATED ZONE MODEL

Parameter	Aquifers[a]	Non-Aquifers[b]
Thickness, ft	1-500[c]	1-500[c]
Soil Moisture	0.1-0.2	0.05-0.45
Total Porosity	0.1-0.4	0.05-0.50
Permeability, cm/sec	$10^{-1} - 10^{-4}$	$10^{-4} - 10^{-7}$
Pore-Size Index	2-5	1-2

[a] Aquifer materials are defined as those that have flow velocities $\geq$ 1m/yr.

[b] Non-aquifers have flow velocities<1m/yr.

[c] Site-specific thickness (depth to water table) included in Table B-4.

TABLE B-4
LIST OF SITE-VISIT FACILITIES AND CORRESPONDING WATER-TABLE DEPTHS, SUBREGIONS, SETTINGS, AND ASSIGNED FLOW FIELDS

Facility I.D.	Water-Table Depth (ft)	Hydrogeologic Subregion	Generic Hydro-Settings	Flow Fields
CTD001160811	2	11	1,5,7	C,D,G,I
CTD001159300	2	11	1,5,7	C,D,G,I
CTD051320372	5	9A	1,3,7,8	C,F,I
CTD003935905	10	11	1,5,7	C,D,G,I
CTD056748205	50	9A	1,3,7,8	C,F,I
CTD001180462	5	9B	2,4	B,F
CTD002344257	5	9B	2,4	B,F
NJD079320495	5	9A	1,3,5	C,F,G
NJD002521961	10	10A	1-8	B,C,F,G,H,I
VAD065385296	20	10A	1-8	B,C,F,G,H,I
PAD004344222	10	8A	2,4	A,B,F
PAD004498010	10	6B	2,4,8	B,F,I
WVD005005509	10[a]	6B	2,4,8	B,F,I
NCD003154010	40	8A	2,4	A,B,F
SCD036155372	25	8A	2,4	A,B,F
SCD003345683	25[a]	8A	2,4	A,B,F
SCD082728347	20	10D	1,2,7,8	B,D,I
FLD004073177	15(100)[b]	10D	1,2,7,8	B,D,I
FLD043117522	15	10D	1,2	B,C,D,F
FLD047966593	15(100)[b]	10C	2,4,8	B.F.I
GAD067560870	50	8A	2,4	A,B,F
GAD000814541	50	8A	2,4	A,B,F
OHD004222030	11	7B	2,4,8	B,F,I
OHD990747859	32	7C	1,2,3,7	B,C,G,I
OHD068932011	52	7A	1,3,7	C,F,I
MID000724831	1	11	1,5,7	C,D,G,I
MID000721753	60	7B	2,4,8	B,F,I
MID005358130	80	7A	1,3,7	C,F,G,I
IND058689241	18	7A	2,3,7,8	C,F,I
IND000780544	15	7A	1,3,7	C,F,I
IND093220861	23	7B	2,4,8	B,F,I
IND000810903	80	7C	1,2,3,7	B,C,G,I
IND005159199	16	7D	2,3,4,7,8	B,F,I
ILD041550567	3	7D	2,3,4,7,8	B,F,I
ILD045063450	10	7D	2,3,4,7,8	B,F,I
IAD000223354	3	7D	2,3,4,7,8	B,F,I
IAD005173992	10[a]	11	1,5,7	C,D,G,I
KYD055832091	30	11	1,5,7	C,D,G,I
ALD000770214	15	6C	1,2,3,4,7,8	B,E,F,I
ALD004009007	50	11	1,5,7	C,D,G,I

TABLE B-4 (Cont'd)

LIST OF SITE-VISIT FACILITIES AND CORRESPONDING WATER-TABLE DEPTHS, SUBREGIONS, SETTINGS, AND ASSIGNED FLOW FIELDS

Facility I.D.	Water Table Depth (ft)	Hydrogeologic Subregion	Generic Hydro-Settings	Flow Fields
ALD000622464	25[a]	10A	1-8	B,C,F,G,H,I
LAD008058471	5	10B	2,4,8	A,B,F,I
LAD008179707	5	10B	2,4,8	A,B,F,I
LAD008186579	5	10B	2,4,8	A,B,F,I
LAD008184137	2	11	1,5,7	C,D,G,I
TXD000327429	10[a]	10A	1-8	B,C,F,G,H,I
TXD000782698	20	10A	1-8	B,C,F,G,H,I
TXD007330202	20	10A	1-8	B,C,F,G,H,I
TXD072181381	5	10A	1-8	B,C,F,G,H,I
TXD026040709	5	10A	1-8	B,C,F,G,H,I
TXD008117749	10	10A	1-8	B,C,F,G,H,I
OKD990695991	54	6B	2,4	A,B,F
OKD057705972	27	6B	2,4	A,B,F
OKD000396549	28	11	1,5,7	C,G,I
OKD980627046	39(390)[b]	6D	1,2,3	B,C,F
OKD000803205	25	6B	2,4	A,B,F
OKD065438376	5	6B	2,4	A,B,F
WYD991501086	30		1,2,3,6	B,C,F,H
NM5890110518	455	2A	1,2,7,8	B,C,I
ORD089452353	500	3B	1,2,5,6	B,C,D,G,H
WAD009276197	20[a]	2A	1,5,8	C,D,H,I
CA7570024508	139	2A	1,2,7,8	B,C,D,G,H
CAD000629998	63	2A	1,2,7,8	B,C,D,G,H
CAD990769465	50	2A	1,2,7,8	B,C,D,G,H
CAD000060012	50	2B	2,4	A,B,F
CAD009108705	5	2B	2,4	A,B,F
CAD041844002	4	2A	2,3,8	B,F,I
CAD009438300	6	2A	2,3,8	B,F,I
CAD009125923	43	2A	2,3,8	B,F,I
CAD009205097	12	2A	2,3,8	B,F,I

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[a] Depth estimated by G&M; depth to water not available in GCA database.

[b] Depth estimated by G&M; depth to water provided by GCA database (in parentheses) represents deep aquifer

Each literature survey study area was assigned a hydrogeologic generic setting that best characterizes the study area. Figure B-4 is a schematic drawing that shows eight generic hydrogeologic settings identified from the data base. As shown, aquifer materials are divided into two classes representing a primary and secondary status. Primary aquifers generally represent more permeable materials, higher velocities, and large-scale groundwater development. Secondary aquifers represent poorly productive aquifers with smaller velocities and limited groundwater development.

Although each generic setting is multilayered, settings 1 and 2 are essentially equivalent to a single aquifer layer model. As suggested by Figure B-4, this is either due to very low permeability of the underlying non-aquifer materials or due to upward flow from the lower aquifer through confining bed non-aquifers. In either of these cases, G&M assumed that plume growth would be limited to the uppermost aquifer layer.

The generic setting that occurs most frequently in the data base is a single shallow aquifer represented by generic settings 1 and 2. The preponderance of these settings is attributed to the fact that the data base represented is biased toward aquifers, since the studies are primarily water-supply oriented. If these settings were the only ones applied to all of the site-visit facilities, it would bias model output towards a set of worst-case scenarios. Even though many site-visit facilities may be located over shallow aquifers, it is realistic to also include other less conservative settings.

The data in Table B-2 were not averaged and used directly with the generic settings in the development of the generic flow fields for the transport model. Some massaging and inspection of data were needed before generic flow field scenarios were developed. Velocity distributions for horizontal flow in primary and secondary aquifers were examined by preparing a histogram of velocities shown in Figure B-5a. This figure shows a six-order-of-magnitude range of a log-normal distribution for horizontal velocity. A similar histogram was prepared for vertical velocities,

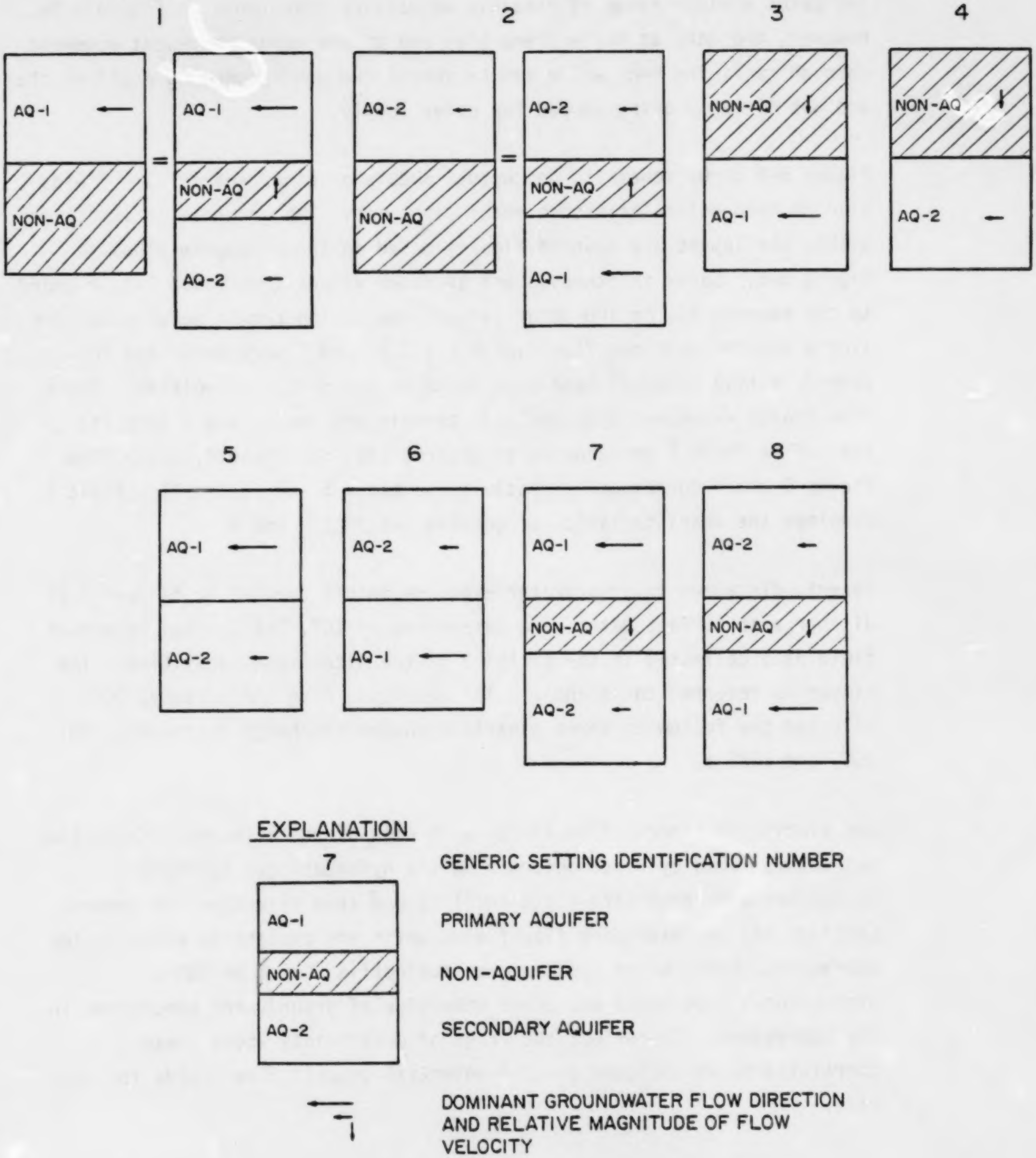

1
AQ-I
NON-AQ
=
AQ-I
NON-AQ
AQ-2
2
AQ-2
NON-AQ
=
AQ-2
NON-AQ
AQ-I
3
NON-AQ
AQ-I
4
NON-AQ
AQ-2
5
AQ-I
AQ-2
6
AQ-2
AQ-I
7
AQ-I
NON-AQ
AQ-2
8
AQ-2
NON-AQ
AQ-I
EXPLANATION
7
GENERIC SETTING IDENTIFICATION NUMBER
AQ-I
PRIMARY AQUIFER
NON-AQ
NON-AQUIFER
AQ-2
SECONDARY AQUIFER
DOMINANT GROUNDWATER FLOW DIRECTION AND RELATIVE MAGNITUDE OF FLOW VELOCITY

Figure B-4. Eight Generic Hydrogeologic Settings Showing Sequence of Water-Bearing Materials and Dominant Groundwater Flow Directions.

through non-aquifer materials. This histogram, shown in Figure B-5b, indicates a wider range of possible velocities than those in Figure B-5a. However, the data at the extreme high end of the range represent movement through confining beds which can be considered poor-producing aquifers that are not directly being pumped for water supply.

Figure B-6 shows schematic conceptual models of nine generic flow fields used to help define transport model scenarios. The groundwater velocities within the layers are rounded figures based on the histogram plots in Figure B-5. Layer thicknesses are averaged values from Table B-2, rounded to the nearest 10- or 100-meter value. Due to the common occurrence of a single aquifer setting, flow fields A,B,C,D, and E were developed to provide a five-order-of-magnitude range on horizontal velocities. These flow fields represent hydrogeologic generic settings 1 and 2 from Figure B-4. Flow field F corresponds to generic settings 3 and 4, while flow fields G and H correspond directly to settings 5 and 6, and flow field I combines the characteristics of generic settings 7 and 8.

Generic distances to groundwater exposure points (wells) or to points of discharge to surface water were determined by ICF, Inc., based on actual field data collected in the vicinity of the site-visit facilities. The reader is referred to Appendix C for details. From their study, ICF selected the following three generic exposure/discharge distances: 60, 600, and 1500 m.

Correlation of generic flow fields with each of the site-visit facilities was accomplished by first determining the hydrogeologic subregion associated with each site-visit facility and then selecting the generic settings and corresponding flow fields which are thought to exist in the subregion. Correlation was somewhat subjective, based on G&M's professional experience and prior knowledge of groundwater conditions in the subregions. To reflect the range of uncertainty about these correlations, we included several potential generic flow fields for each site.

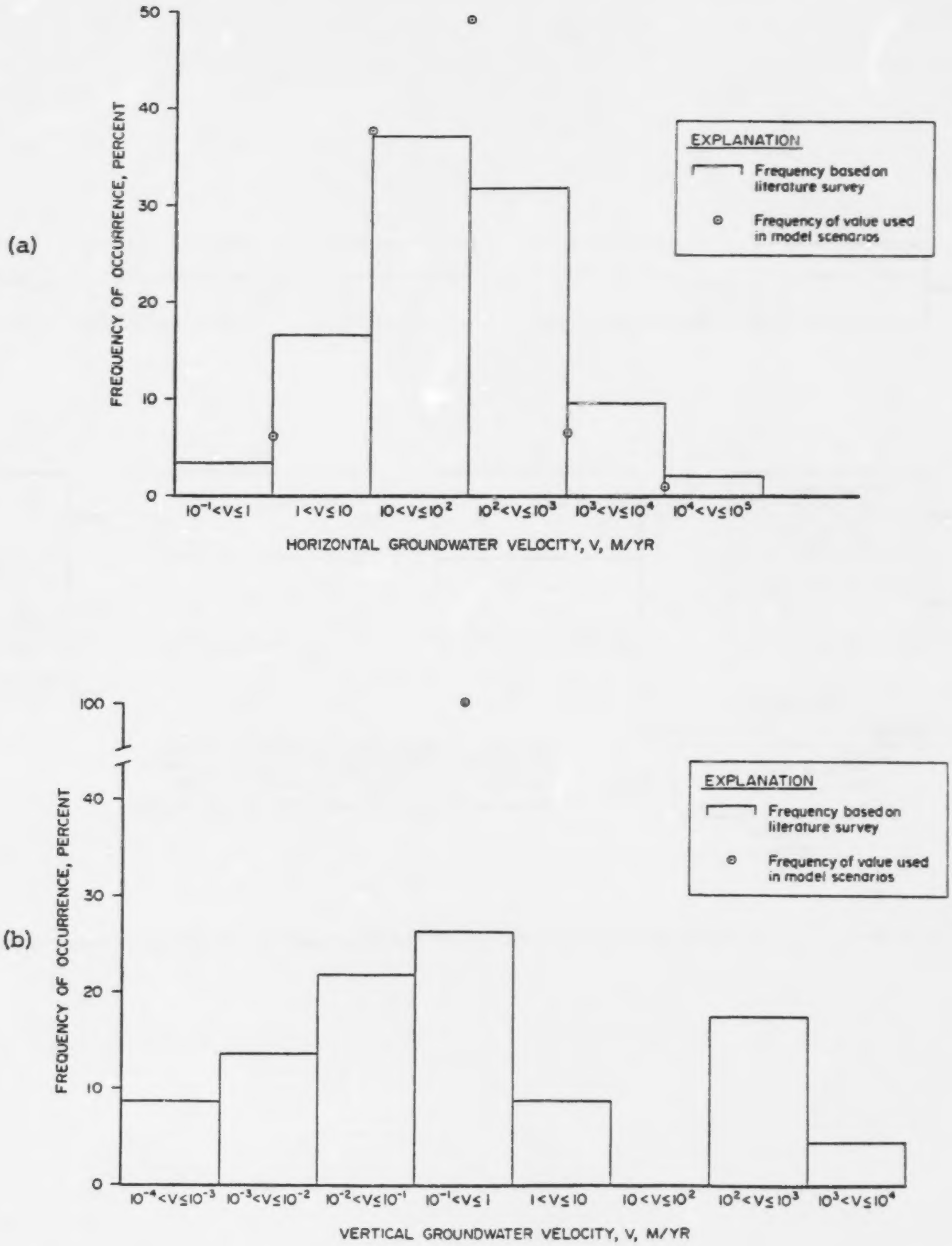
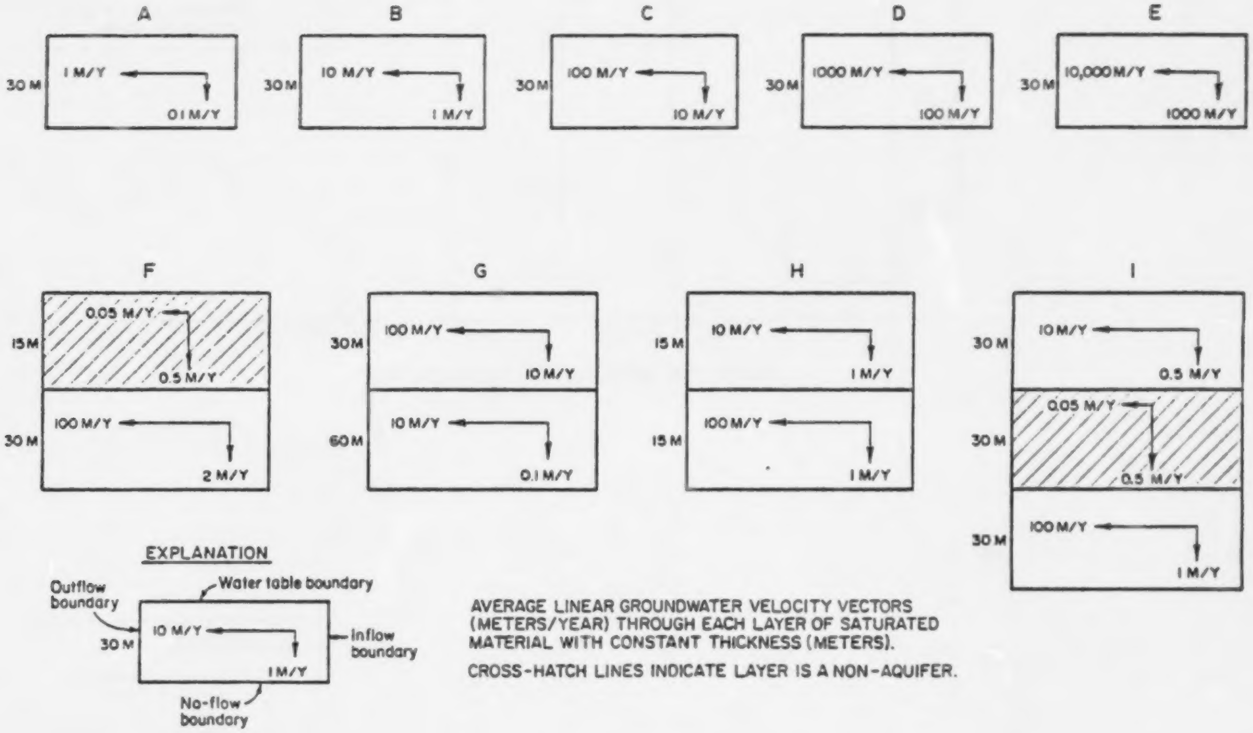


Figure B-5. Histograms of Groundwater Flow Velocities Representing
(a) Horizontal Flow Through Aquifers, and
(b) Vertical Flow Through Non-Aquifers.


A
30 M
1 M/Y
0.1 M/Y
B
30 M
10 M/Y
1 M/Y
C
30 M
100 M/Y
10 M/Y
D
30 M
1000 M/Y
100 M/Y
E
30 M
10,000 M/Y
1000 M/Y
F
15 M
0.05 M/Y
0.5 M/Y
30 M
100 M/Y
2 M/Y
G
30 M
100 M/Y
10 M/Y
60 M
10 M/Y
0.1 M/Y
H
15 M
10 M/Y
1 M/Y
15 M
100 M/Y
1 M/Y
I
30 M
10 M/Y
0.5 M/Y
30 M
0.05 M/Y
0.5 M/Y
30 M
100 M/Y
1 M/Y
EXPLANATION
Outflow boundary
Water table boundary
30 M
10 M/Y
1 M/Y
Inflow boundary
No-flow boundary

AVERAGE LINEAR GROUNDWATER VELOCITY VECTORS (METERS/YEAR) THROUGH EACH LAYER OF SATURATED MATERIAL WITH CONSTANT THICKNESS (METERS).

CROSS-HATCH LINES INDICATE LAYER IS A NON-AQUIFER.

Figure B-6. Nine Generic Groundwater Flow Fields Used in Transport Model Scenarios.

Table B-4 lists all of the site visit facilities with the corresponding hydrogeologic subregions, generic settings, and matched generic flow fields. Facilities are listed on the basis of location from east to west and north to south starting with New England states and finishing with California. Flow field velocities were combined with the matched list of generic flow fields in Table B-4 to provide a histogram of the frequency of occurrence of aquifer and non-aquifer velocities. As shown in Figure B-5, velocities selected for modeling have a distribution comparable to the distribution of the velocities selected from the literature.

2.2.2 Transport Characteristics

Transport characteristics include contaminant mobility in both saturated and unsaturated materials and dispersion within saturated materials. Corresponding model parameters for these two characteristics are the velocity retardation factor and the dispersivity of the porous media. Retardation factors were determined for chemicals in the data base by ICF, Inc (see Appendix F). Dispersivity data were developed by G&M on the basis of literature values and conservative assumptions. Other physical processes that affect transport such as biodegradation and hydroloysis were assumed to be negligible by G&M. Hydrolysis, however, is taken into account in the integrated Liner Location Model (see Appendix G).

Values of the retardation factor ranged over five orders of magnitude. Contaminants were grouped into four mobility classes on the basis of the value of the retardation factor. There was reasonable concern by G&M that contaminants in the least mobile class would probably not move a significant distance in a 400-year simulation (includes a 200-year facility mass-release simulation and 200-year groundwater mass-transport simulation). Model results confirmed the appropriateness of omitting simulations for the least mobile class. The remaining three mobility classes and corresponding average retardation factors are as follows:

- Class No. 1 - 1.3
- Class No. 2 - 32
- Class No. 3 - 360

Dispersivity values for the saturated zone are based on information compiled by Anderson (1979), Gillham and Cherry (1982), and Walton and Davis (1982). Based on these sources, dispersivity is known to vary with direction in space, the relative permeability of the material, and the length of the flow path. Dispersivity also increases with increasing levels of heterogeneity in the earth materials.

Dispersitivities determined from laboratory tests of homogeneous/isotropic (with respect to permeability) earth materials with flow-path lengths of less than a few meters range from approximately 10^{-4} to 10^{-2}m. Field determinations which involved one or more closely spaced wells in aquifer materials that, to some degree, are generally heterogeneous and anisotropic, range from about 1 to 30 m. Dispersivities determined for calibrated models with simulated flow paths on the order of 10's to 1000's of meters, range from approximately 20 to 200 m and generally represent heterogeneous/anisotropic aquifers. As discussed earlier, G&M has assumed that the generic flow field represents homogeneous/isotropic materials; however, dispersivities for such materials have not been determined for flow path lengths of the scale used in our generic settings. For these reasons, G&M selected values from the middle range; i.e., from the range representing field tests, to represent dispersivities in the model.

For relatively permeable aquifer materials, dispersivity in the horizontal direction was assigned values of 2,4, and 7.5 m for respective exposure/discharge point distances of 60, 600, and 1500 m. These values reflect a linear increase in dispersivity with length of flow path. Vertical dispersivity in aquifer materials was generally assigned values equal to 0.1 of the horizontal dispersivity and was not related either to layer thickness or flow path length. The less permeable non-aquifer materials were assigned values of dispersivity equal to 0.5 m in the vertical direction and 0.1 m in the horizontal direction. Dispersivity in non-aquifers was considered independent of both thickness and distance to the exposure/discharge points for all scenarios.

It should also be mentioned that dispersivity in the vertical direction in aquifers associated with multi-layer scenarios was set to 0.01 of the dispersivity in a horizontal direction. This was done to limit the dispersion of particles back into overlying layers. The reader will recall that the magnitude of velocity and dispersion vectors applied to a particle is determined in the model by the layer in which a particle resides. When particles moving within a aquifer are dispersed vertically back into an overlying non-aquifer, an artificially long time period is required for the smaller vectors to transport the particle back into the aquifer. Small values of vertical dispersivity essentially eliminates this model-generated problem. Because contaminant concentrations at an exposure well are vertically averaged within an aquifer layer, this change does not create errors in the concentrations computed by the model.

3. METHODOLOGY OF SUBSURFACE TRANSPORT MODELING

3.1 Unsaturated Zone Model Description

To simulate transport time through the unsaturated zone, G&M selected the wetting front model described in McWhorter and Nelson (1979). This model assumes that the unsaturated zone initially has a volumetric water content equal to field capacity Θ_r. Infiltration of water through the liner into the unsaturated zone (i.e., the leachate release rate) produces a wetting front that moves downward to the water table. The wetting front is defined as the transition zone between underlying material with water content Θ_r, and overlying material with water content Θ_f.

The value of Θ_f depends on the rate at which water is supplied and the saturated permeabilities of the liner and the materials in the unsaturated zone. It is equal to total porosity when the supply rate through the liner is equal to or greater than the permeability of materials in the unsaturated zone (McWhorter and Nelson, 1979). It will be close to the residual water content when the liner has a smaller permeability than that of the unsaturated zone.

The moisture content is determined with the following expression (McWhorter and Nelson, 1979):

$$\Theta_f = (n - \Theta_r)\ (q/K)^{x/(2+3x)} + \Theta_r \qquad (1)$$

where

Θ_f = Water content above wetting front, (dimensionless)

n = Porosity, (dimensionless)

Θ_r = Water content below wetting front (dimensionless)

q = Leakage rate, or Darcian flux, at liner, (L/T)

K = Hydraulic conductivity, (L/T)

x = Pore-size distribution index, (dimensionless).

Wetting front travel time through the unsaturated zone is estimated with the following expression:

$$t = L\ (\Theta_f - \Theta_r)\ /q \qquad (2)$$

where, Θ_f, Θ_r, and q are defined above, and

t = Travel time, (T)

L = Distance wetting front has moved from the liner, (L).

Equations 1 and 2 above can be combined to provide the following expression:

$$t = (L/q)\ (n - \Theta_r)\ (q/K)^{x/(2 + 3x)}. \qquad (3)$$

If the retardation of contaminants is to be considered in the time lag for mass transport to the water table, t_r, Equation 3 should be adjusted by a retardation factor, R_d, as follows:

$$t_r = tR_d. \qquad (4)$$

It is assumed that during the time in which contaminants are migrating from the liner to the water table, all parameters in Equations 3 and 4 are being held constant. Values for model input parameters were taken as midranges of the values given in Table B-3, as explained more fully in Appendix G.

3.2 Unsaturated Zone Model Results

The effect that model parameters have on output was evaluated by inspection of Equations 3 and 4 and by examination of the range of values assigned to the model parameters. Table B-5 summarizes the mathematical relationships between travel time through the unsaturated zone and seven model parameters. As shown in this table, travel time is most affected by thickness of the unsaturated zone, specific discharge of leachate into the unsaturated zone, and the retardation factor. These three parameters have values that range over several orders of magnitude. The least sensitive parameters include porosity, soil moisture, permeability, and pore-size distribution index. These parameters are assigned values having relatively narrow ranges. Because these variables are relatively insensitive, average or middle range values for these last four parameters were recommended for the purposes of this project.

3.3 Saturated Zone Model Description

To simulate up to 200 years of mass transport through multi-layered groundwater flow fields in this project, G&M selected the Random-Walk model of Prickett, Naymik, and Lonnquist (1981). This particle-tracking computer code, developed by the authors at the Illinois State Water Survey, is well documented and has been tested against several analytical solutions.

TABLE B-5
MATHEMATICAL RELATIONSHIPS AND GENERAL SENSITIVITY OF UNSATURATED ZONE TRAVEL TIME TO MODEL PARAMETERS

Model Parameter	Mathematical Relation to Travel Time	Range of Parameter Values		Effect on Travel Time
		Aquifers	Non Aquifers	
Thickness	Directly proportional	1 - 500 ft	1 - 500 ft	Major
Leachate Discharge	Inversely proportional	a	a	Major
Retardation Factor	Directly proportional	1.3 - 360	1.3 - 360	Major
Porosity and Soil Moisture	Difference in these is directly proportional	0.1 - 0.4	0.05 - 0.5	Minor
		0.1 - 0.2	0.05 - 0.45	Minor
Permeability	Inversely related, but not linear	10^{-1} - 10^{-4} cm/sec	10^{-4} - 10^{-7} cm/sec	Minor
Pore-Size Index	Positively related, but not linear	2 - 5	1 - 2	Insignificant

[a] Leachate releases range over several orders of magnitude.

When using the Random-Walk model, the flow field is subdivided into a grid network of smaller subregions. The groundwater velocities are represented by vectors in each of the subregions. The Random-Walk model is capable of generating such a velocity field using a numerical or analytical flow model. In this project, however, the velocity field was pre-defined as a generic flow field which was input to the model.

As shown on Figure B-7, each flow field was analyzed in cross section (unit thickness of 1 m) and was assumed to be oriented parallel to the local hydraulic gradient at any site. Layers within the flow field were composed of isotropic and homogeneous materials and were each assigned a velocity distribution and a separate dispersivity. No attempt was made to rigorously conserve the mass of water flowing between layers. However, velocity vectors were assigned values that insure an approximate, if not exact, water mass balance between layers.

The set of generic flow fields represents an idealized set of hydrogeologic site conditions. Flow fields, for example, are composed of layers having simple and regular geometries, each of which are assigned uniform (homogeneous) distributions of groundwater velocity, porosity and dispersivity. Limitations on our knowledge of these characteristics at existing sites nationwide prevents us from developing a set of more realistic generic flow fields that encompass the full range of nonuniform (heterogeneous) distributions of these parameters. Also, this constraint prevents us from analyzing generic settings characterized by groundwater flow through discrete fractures (i.e., anisotropic conditions). The only way anisotropy is permitted in the model is to allow the parameter dispersivity to vary with direction; however, as discussed later, this has little effect on model output other than to control vertical particle movement between multiple layers.

The Random-Walk code begins a simulation by introducing a suitable number of particles representing a finite amount of mass into the velocity field. Particles are introduced at random over a specified period of time called a

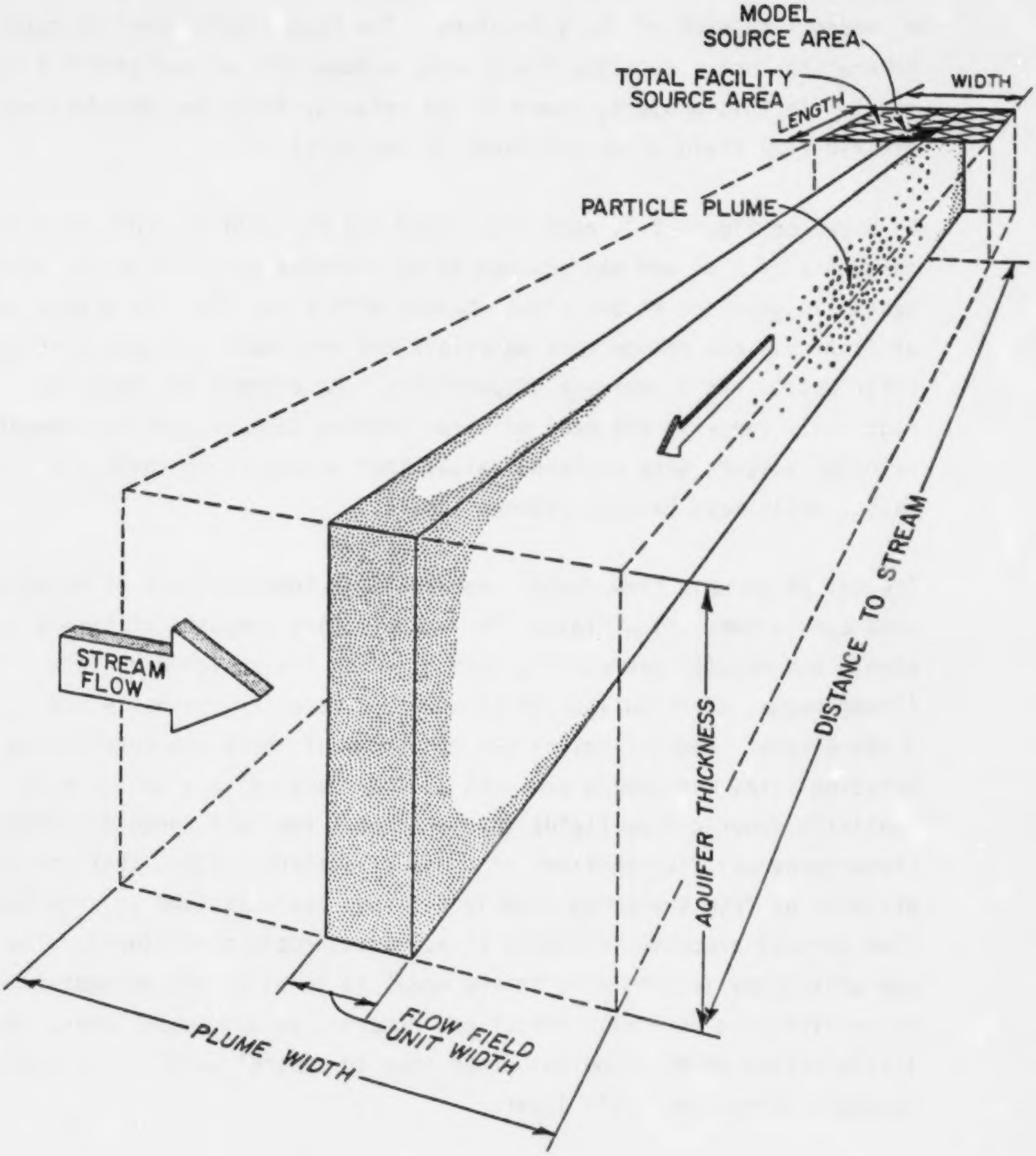

MODEL SOURCE AREA
TOTAL FACILITY SOURCE AREA
WIDTH
LENGTH
PARTICLE PLUME
STREAM FLOW
DISTANCE TO STREAM
AQUIFER THICKNESS
FLOW FIELD UNIT WIDTH
PLUME WIDTH

Figure B-7. Orientation of a Generic Flow Field with Respect to the Contaminant Source and the Surface Water Outflow Boundary.

"time step." Transport of these particles through the flow field is divided into two stages. In the first stage, called the "advective stage," the particles are moved in the direction of groundwater flow in sequential time steps. The distance moved in each time step is equal to the velocity multiplied by the duration of the time step. At the end of each time step, the particles are again moved to simulate the dispersion process. In this second "dispersive stage,", the model assumes that disperson is a random process that would follow a normal distribution function. Each particle is given a random dispersive displacement based on the value for the longitudinal and transverse disperson coefficients, the distance moved in the advective stage, and a random number between zero and one. The distance moved in the advective stage is added to the distance moved in the dispersive stage and the new coordinates for each particle are stored at the end of each time step.

The mobility-determining retardation factors associated with three contaminant mobility classes were applied to all layers uniformly in a scenario simulation. The retardation factors are used to transform the groundwater velocity vectors into contaminant velocity vectors at any point within the flow field. The retardation factors also reduce the value of the disperson coefficients which are directly proportional to dispersivity and contaminant velocity.

The source of contamination was standardized in order to permit extrapolating output to a wide range of specific sources at site-visit facilities. The source was modeled as a 1-m x 10-m strip at one end of the vertical flow field, along which 1,000 particles were released during the first year of simulation time. Each particle was assigned the value of 1 gm so that the standard mass input would be 1 Kg per year over the 10 m^2 source area.

The Random-Walk code was modified in order to accommodate two general cases of particle input. When horizontal groundwater velocities are large enough to cause particles to appear within one year at an exposure point, particles must be introduced in smaller time steps than one year to allow the calculation of concentrations and mass loadings within the first year. When groundwater velocities are sufficiently slow to prevent particles from appearing at an exposure point within the first year, the source is modeled as a single one-year time step.

All of the contaminant mass that is introduced into the flow field at the source will eventually migrate to downgradient subregions of a flow field. Because the published code does not physically remove particles from the flow field, particles introduced at the upgradient end will accumulate at the downgradient end of the flow field. For this reason, the most downgradient model grid subregion in each aquifer of interest was set aside for calculating concentrations and mass loadings.

The published code was modified slightly to handle multiple layers and a vertically-oriented flow field. In principle, the modified code simulated particle movement and contaminant concentration in the same way that these are done in the published code for an exposed well. However, a new subroutine was written to facilitate calculations at hypothetical wells that produce water only from a single aquifer layer. Like the published code, the new subroutine uses the contaminant mass and volume of water flowing into the downgradient subregion per time step to determine the concentration of contaminants in water by the hypothetical well. It was further assumed that the well is surrounded by contaminated water and that is produces water from the full thickness of only a single aquifer layer.

This conservative assumption implies that no dilution can occur in the well from the mixing of contaminants on the upgradient side of the well with uncontaminated water on either the downgradient side or from another aquifer.

To calculate concentration at a hypothetical well, particles entering the downgradient subregion were counted and converted to a mass flux for each time step. The mass flux into the subregion was divided by the volumetric flux of water into the subregion to yield an average concentration over each time step. Like the published code, the new subroutine does not partition the mass between a liquid solute phase and a solid matrix adsorbed phase. However, retarded movement of particles relative to groundwater flow into the region serves to indirectly account for partitioning of the mass, so that the correct concentration is obtained (see list of code and discussion in Supplemental Document to Appendix B). Table B-6 is an example of output in the form of a table of concentrations with time at a hypothetical well located 60 m from a facility.

For calculating surface water mass loading, it was assumed that particles entering the downgradient subregion were instantaneously released to a surface-water body. The program was written to count the total number of particles accumulating within the subregion and to equate them to the total mass that is accumulating in the surface-water body. Table B-6 shows an example of output of the cumulative mass load with time. Because concentrations and mass loads are calculated by counting particles within the same subregion, the output data could be checked by hand to insure a mass balance between concentrations and mass loadings. Tabulated output was also checked against computer-printed maps of the particles residing in each grid subregion at the end of each time step (see Supplementary Document for an example).

3.4 Saturated Zone Model Results

Each transport scenario simulated with the Random-Walk model was identified by one of nine generic flow fields, one of three mobility classes, and one of three generic exposure/discharge point distances. Out of a total of 81 possible combinations of these three elements, 35 combinations result in contaminants arriving only after the 200-year time limit on model simulations. For this reason, G&M simulated only 46 of the 81 possible scenarios. Identification numbers for these scenarios are listed in Table B-7. Tables of output for these 46 simulations are included in the separately bound Supplementary Document.

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Table B-6

EXAMPLE OF RANDOM-WALK MODEL OUTPUT

```
SCENARIO - A-1-60


 TIME AND CONCENTRATIONS FOR WELL EXPOSURE
                                                      TIME AND MASS LOADING TO SURFACE WATER BODY
  TIME(YR)    DELTA PARTICLES   CONCENTRATION (MG/L)
                                                            TIME(YRS)    CUMULATIVE MASS LOAD(KG)

   21.00             0.             0.0000
   26.00             1.              .0268                    21.00            0.000
   31.00             1.              .0268                    26.00             .001
   36.00             4.              .1068                    31.00             .002
   41.00            10.              .2668                    36.00             .006
   46.00             8.              .2132                    41.00             .016
   51.00            15.              .4000                    46.00             .024
   56.00            49.             1.3068                    51.00             .039
   61.00            57.             1.5200                    56.00             .068
   66.00            88.             2.3466                    61.00             .145
   71.00            89.             2.3732                    66.00             .233
   76.00            77.             2.0532                    71.00             .322
   81.00            77.             2.0532                    76.00             .399
   86.00            75.             2.0000                    81.00             .476
   91.00            65.             1.7332                    86.00             .551
   96.00            80.             2.1332                    91.00             .616
  101.00            55.             1.4668                    96.00             .696
  106.00            48.             1.2800                   101.00             .751
  111.00            39.             1.0400                   106.00             .799
  116.00            39.             1.0400                   111.00             .838
  121.00            27.              .7200                   116.00             .877
  126.00            17.              .4532                   121.00             .904
  131.00            24.              .6400                   126.00             .921
  136.00            11.              .2932                   131.00             .945
  141.00            11.              .2932                   136.00             .956
  146.00             8.              .2132                   141.00             .967
  151.00             5.              .1332                   146.00             .975
  156.00             7.              .1868                   151.00             .980
  161.00             4.              .1068                   156.00             .987
  166.00             2.              .0532                   161.00             .991
  171.00             1.              .0268                   166.00             .993
  176.00             3.              .0800                   171.00             .994
  181.00             0.             0.0000                   176.00             .997
  186.00             0.             0.0000                   181.00             .997
  191.00             1.              .0268                   186.00             .997
  196.00             0.             0.0000                   191.00             .998
  201.00             0.             0.0000                   196.00             .998
                                                             201.00             .998
```

TABLE B-7
LIST OF 46 TRANSPORT MODEL SCENARIOS SIMULATED WITH THE RANDOM-WALK MODEL[a]

28 Single-Layer Scenarios:

A-1-60[b]
B-1-60
C-1-60
D-1-60
E-1-60
B-2-60
C-2-60
D-2-60
E-2-60
C-3-60
D-3-60
E-3-60

B-1-600
C-1-600
D-1-600
E-1-600
C-2-600
D-2-600
E-2-600
D-3-600
E-3-600

B-1-1500
C-1-1500
D-1-1500
E-1-1500
D-2-1500
E-2-1500
E-3-1500

18 Double- and Triple-layer Scenarios:

F-1-60
G-1-60
G-2-60
G-3-60
H-1-60
H-2-60
I-1-60
I-1-60A
I-2-60

F-1-600
G-1-600
G-2-600
H-1-600
I-1-600

F-1-1500
G-1-1500
H-1-1500
I-1-1500

---

[a] Tables of model output presented in Supplemental Document to Appendix B.

[b] Flow field scenario - Contaminant mobility class - Distance to exposure point, meters

3.4.1 Rules for Interpreting Model Output

There are several basic rules that should be followed when reading model output from the Random-Walk model. These rules deal with the following three areas:

- Output at discrete points in time
- Negative numbers in the output tables
- Mass loading to surface-water bodies for multi-layer cases.

The standardized contaminant mass input to each of the model scenarios produces a standard breakthrough curve in the form of tables similar to that shown in Table B-6. Figure B-8 is a plot of the data in Table B-6 and represents the standard breakthrough curve for scenario A-1-60. As shown in the figure, the model produces concentrations at discrete points in time which approximate the shape of the breakthrough curve. Particle-tracking models typically do not produce smooth output. If smooth output is desired, a curve must be fit to the data as shown in Figure B-8.

The shape of the standard breakthrough curve is typically asymmetrical. In single-layer scenarios, the shape is caused by the fact that late-arriving particles from the upgradient of the line sources are subject to a longer flow path and more disperson than early-arriving particles originating at the downgradient end of the source. In multi-layered scenarios involving flow fields F and I, the assymetry is also caused by the dispersion of some particles from an aquifer into the non-aquifer and subsequent slow release back into the aquifer of interest.

Negative numbers in the output tables are caused by two processes. The first process involves continued dispersive movement of particles after they have entered the most downgradient model grid subregion. Particles can disperse back out of the subregion at the end of a time step resulting in a negative mass flux into the subregion. This condition is most likely to occur when most of the particles have migrated into this subregion. This mechanism produces small negative numbers in the "Delta Particle" column of the output table at later times in the simulation.

TABLE B-7
LIST OF 46 TRANSPORT MODEL SCENARIOS SIMULATED WITH THE RANDOM-WALK MODEL[a]

---

28 Single-Layer Scenarios:

A-1-60[b]
B-1-60
C-1-60
D-1-60
E-1-60
B-2-60
C-2-60
D-2-60
E-2-60
C-3-60
D-3-60
E-3-60

B-1-600
C-1-600
D-1-600
E-1-600
C-2-600
D-2-600
E-2-600
D-3-600
E-3-600

B-1-1500
C-1-1500
D-1-1500
E-1-1500
D-2-1500
E-2-1500
E-3-1500

18 Double- and Triple-layer Scenarios:

F-1-60
G-1-60
G-2-60
G-3-60
H-1-60
H-2-60
I-1-60
I-1-60A
I-2-60

F-1-600
G-1-600
G-2-600
H-1-600
I-1-600

F-1-1500
G-1-1500
H-1-1500
I-1-1500

---

[a] Tables of model output presented in Supplemental Document to Appendix B.

[b] Flow field scenario - Contaminant mobility class - Distance to exposure point, meters

3.4.1 Rules for Interpreting Model Output

There are several basic rules that should be followed when reading model output from the Random-Walk model. These rules deal with the following three areas:

- Output at discrete points in time
- Negative numbers in the output tables
- Mass loading to surface-water bodies for multi-layer cases.

The standardized contaminant mass input to each of the model scenarios produces a standard breakthrough curve in the form of tables similar to that shown in Table B-6. Figure B-8 is a plot of the data in Table B-6 and represents the standard breakthrough curve for scenario A-1-60. As shown in the figure, the model produces concentrations at discrete points in time which approximate the shape of the breakthrough curve. Particle-tracking models typically do not produce smooth output. If smooth output is desired, a curve must be fit to the data as shown in Figure B-8.

The shape of the standard breakthrough curve is typically asymmetrical. In single-layer scenarios, the shape is caused by the fact that late-arriving particles from the upgradient of the line sources are subject to a longer flow path and more disperson than early-arriving particles originating at the downgradient end of the source. In multi-layered scenarios involving flow fields F and I, the assymetry is also caused by the dispersion of some particles from an aquifer into the non-aquifer and subsequent slow release back into the aquifer of interest.

Negative numbers in the output tables are caused by two processes. The first process involves continued dispersive movement of particles after they have entered the most downgradient model grid subregion. Particles can disperse back out of the subregion at the end of a time step resulting in a negative mass flux into the subregion. This condition is most likely to occur when most of the particles have migrated into this subregion. This mechanism produces small negative numbers in the "Delta Particle" column of the output table at later times in the simulation.

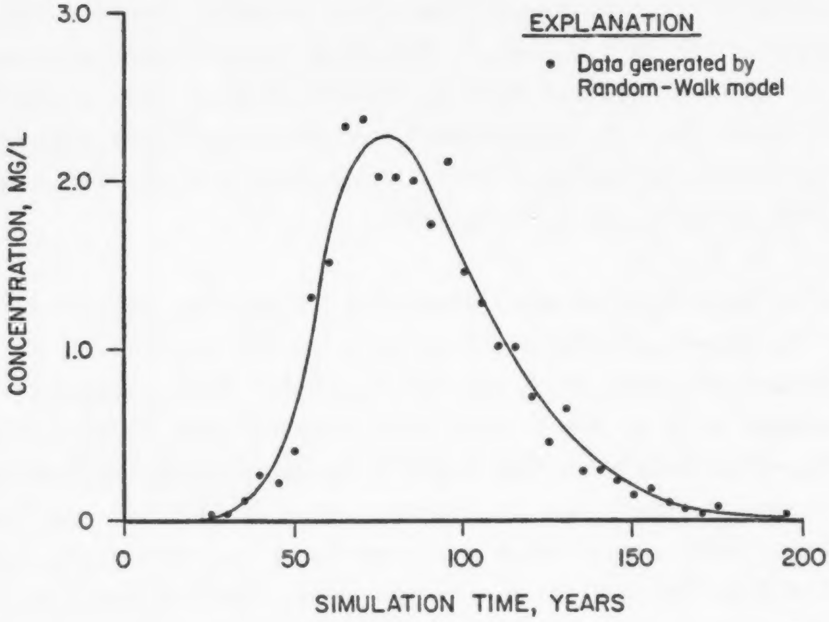

Figure B-8. Standard Breakthrough Curve for Transport Model Scenario A-1-60.

The second process that produces negative numbers occurs in the three-layer flow field for scenario I-1-60A. Owing to the geometry of the model layers and to the direction of groundwater flow though the layers, it is possible that contaminant particles will enter the lower-most aquifer after they have moved greater than 60 m beyond the edge of the facility. Under this condition, contaminants never appear at the hypothetical well located 60 m from the facility. To insure that exposure occurred at this well, the direction of groundwater flow was arbitrarily reversed within the lower aquifer for this scenario. Reversing the direction was handled by assigning a negative velocity in model input. This produces negative flow of water into the downgradient subregion and causes negative numbers to be printed in the output. It is recommended that all negative signs under this scenario simply be ignored.

With multi-layered model scenarios the question arises as to which, if not all, layers contribute contaminants to the hypothetical surface-water body. Figure B-9 shows which aquifer layer(s) is(are) allowed to release contaminants to the surface-water body for each flow-field scenario. For scenarios involving flow field F, it was assumed that the upper non-aquifer layer was absent near the surface water so that only the lower aquifer layer makes contact with and contributes contaminants to the surface water. For flow fields G and H, it was assumed that both aquifer layers contribute contaminants to the surface-water body. For scenarios involving flow fields I, it was assumed that only the uppermost aquifer layer contributed contaminants to the surface-water body. Contaminants reaching the lower-most aquifer which underlies a low-permeability layer would by-pass, or flow underneath any nearby surface-water body.

3.4.2 Effects of Key Parameters

Although a formal sensitivity analysis was not performed in this project, the relationship of model output to several key parameters was examined. Relationships were evaluated by examining time of breakthrough and peak concentrations for all scenarios, and by inspection of standard breakthrough curves for selected scenarios.

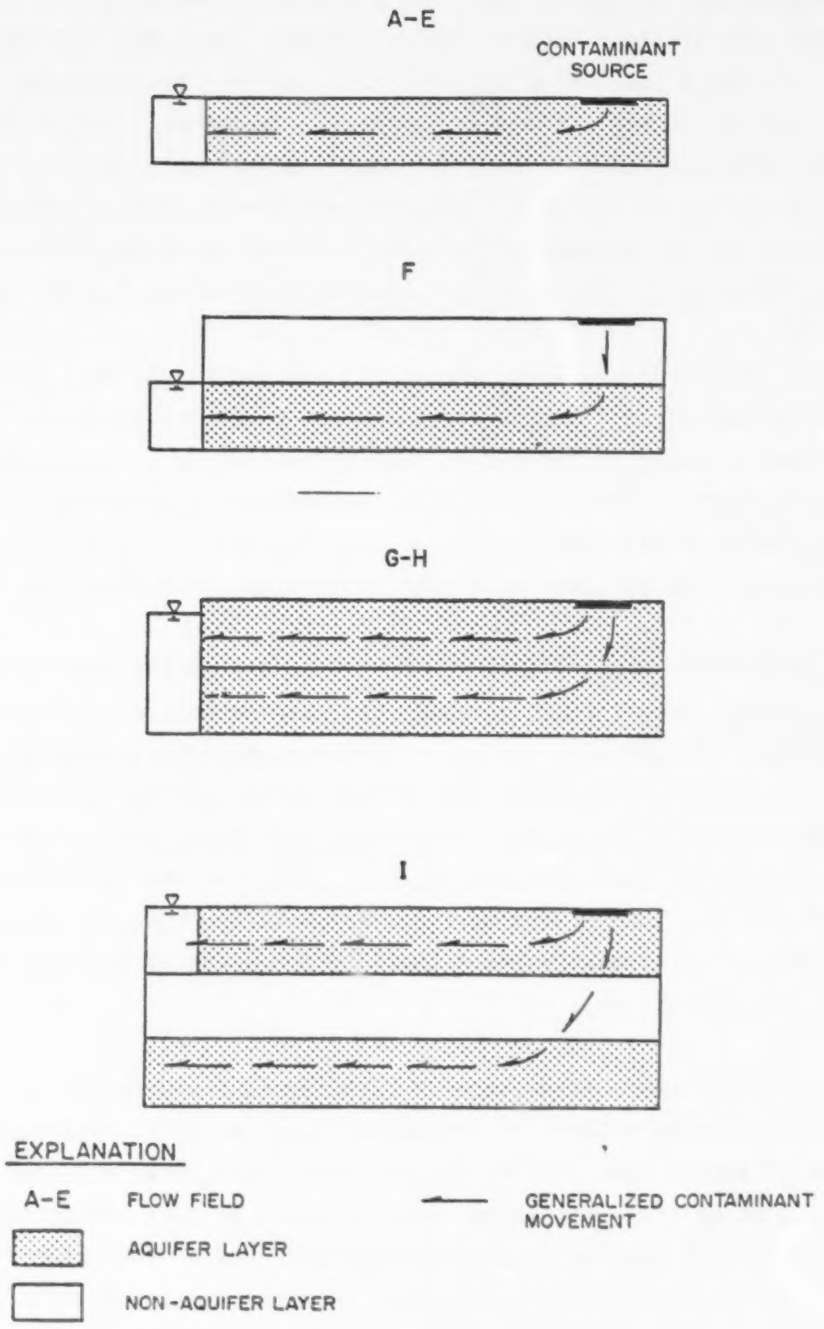
A-E
CONTAMINANT SOURCE
F
G-H
I
EXPLANATION
A-E FLOW FIELD
AQUIFER LAYER
NON-AQUIFER LAYER
GENERALIZED CONTAMINANT MOVEMENT

Figure B-9. Schematic Flow Field Scenarios Showing Model Layers That Can Release Contaminants to Surface Waters.

Table B-8 summarizes contaminant breakthrough times and peak concentrations computed by the Random-Walk model. This table shows the time at which breakthrough of contaminants begin and end along with the time at which a peak concentration occurs. Table B-8 shows that the starting time can be as soon as a small fraction of a year and that breakthrough can extend beyond the 200-year limit set on model simulations. Peak concentrations can range over several orders-of-magnitude, from a value as small as 0.001 to a maximum of 4.1 mg/l. However, the reader should remember that the concentration printed by the model is a random value that only approximates the "true value" represented by the best-fit curve for the output.

Peak concentrations for scenarios B-1-60 and G-1-60-Up (upper layer) show the effect of aquifer thickness on peak concentrations. As suggested by values reported in Table B-8, peak concentration is inversely proportional to thickness. This results from the modeling assumptions that a hypothetical well produces water from the full thickness of the aquifer and that the flow of water is evenly distributed throughout the layer.

Figures B-10 and B-11 show the relationships of the shape and amplitude of a standard breakthrough curve to four key parameters. Figure B-10 shows standard breakthrough curves and corresponding mass-loading curves for three scenarios that show the effects of increasing the distance to the exposure/discharge point. Increasing the travel path of contaminants tends to reduce the peak concentrations by spreading the contaminant breakthrough curve over a longer time period. As shown in Figure B-10b, longer distances and travel times also cause spreading of the mass load to the surface-water body.

Figure B-11 shows three sets of contaminant breakthrough curves that illustrate the effects of increasing flow velocity, retardation factors, and of adding low-velocity layers above the aquifer of interest. Figure B-11a shows that increasing velocity tends to make contaminants arrive sooner, have smaller peak concentrations (due to a greater flux of water and subsequent dilution), and last for shorter periods of time. Slower

TABLE B-8
CONTAMINANT BREAKTHROUGH TIMES AND PEAK CONCENTRATIONS COMPUTED BY THE RANDOM-WALK MODEL

Scenario Identification Number	Starting Time (yr)	Ending Time (yr)	Peak Conc. Time (yr)	Peak Conc. (mg/l)
A-1-60	26	>201	71	2.4
B-1-60	4	20.5	9	2.4
B-2-60	61	>201	201	.12[a]
C-1-60	.35	2.5	1.5	1.5
C-2-60	8	45	19	.10
C-3-60	96	>201	186	.0085
D-1-60	.06	1.12	.34	.20
D-2-60	.80	5.2	2.4	.09
D-3-60	9	51	21	.0085
E-1-60	<.04	1.0	.04	.013
E-2-60	.14	1.36	.42	.019
E-3-60	.75	5.2	2.4	.0089
B-1-600	61	106	81	.60
C-1-600	5.5	12.5	8.5	.57
C-2-600	131	>201	191	.026
D-1-600	.5	2.0	1.4	.15
D-2-600	13.5	29	20.5	.028
D-3-600	151	>201	201	.0023[a]
E-1-600	.06	1.06	.78	.017
E-2-600	1.2	3.5	2.4	.015
E-3-600	16	81	22	.0023
B-1-1500	141	>201	196	.30
C-1-1500	14	27	19.5	.29
D-1-1500	1.3	3.5	2.1	.15
D-2-1500	35	67	48.5	.014
E-1-1500	.14	1.2	.52	.020
E-2-1500	3.8	7.4	5.4	.0087
E-3-1500	37	71	51	.0010
F-1-60	16	135[b]	41	.070
F-1-600	37	111[b]	49	.096
F-1-1500	45	101[b]	59	.095
G-1-60-Up[c]	.40	3.0	1.25	1.2
G-1-60-Lo[d]	1.25	9.75[b]	1.5	.11
G-1-600-Up	6	17	9	.08
G-1-600-Lo	8	101	76	.14

TABLE B-8 (Cont'd)
CONTAMINANT BREAKTHROUGH TIMES AND PEAK CONCENTRATIONS COMPUTED BY THE RANDOM-WALK MODEL

Scenario Identification Number	Starting Time (yr)	Ending Time (yr)	Peak Conc. Time (yr)	Peak Conc. (mg/l)
G-1-1500-Up	19[e]	>201	151	.0011
G-1-1500-Lo	23	>201	186	.11
G-2-60-Up	11	57	21	.10
G-2-60-Lo	27[e]	>201	143	.013
G-2-600-Up	136	>201	201	.0053[a]
G-2-600-Lo	151[e]	>201	191	.0067
G-3-60-Up	121	>201	196	.0072
G-3-60-Lo	146[e]	>201	191	.0027
H-1-60-Up	3.25	19.75	7.75	4.1
H-1-60-Lo	<1.75	16.75[b]	8.5	.11
H-1-600-Up	23.5	46.5[b,e]	38.5	.032
H-1-600-Lo	8.5	98.5[b]	23.5	.13
H-1-1500-Up	26	56[b,e]	36	.069
H-1-1500-Lo	21	136	36	.090
H-2-60-Up	91	>201	181	.18
H-2-60-Lo	21	>201	156	.0037
I-1-60-Up	4.5	19[b]	9	2.4
I-1-60-Lo	0f	0	0	0
I-1-60A-Up	6	21	11	2.0
I-1-60A-Lo[g]	86	>201	151	.017
I-1-600-Up	51	111[b]	81	.25
I-1-600-Lo	41	>201	155	.015
I-1-1500-Up	157	>201	199	.040
I-1-1500-Lo	51	>201	163	.016

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[a] Maximum concentration at end of simulation period represents peak breakthrough concentration

[b] End of breakthrough defined as first occurrence of two consecutive time steps with zero or negative concentrations

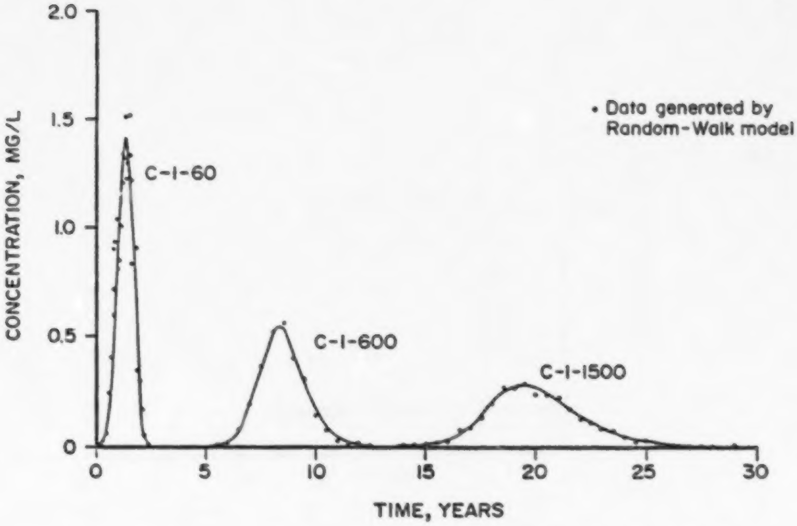
[c] Up = Upper Aquifer Layer

[d] Lo = Lower Aquifer Layer

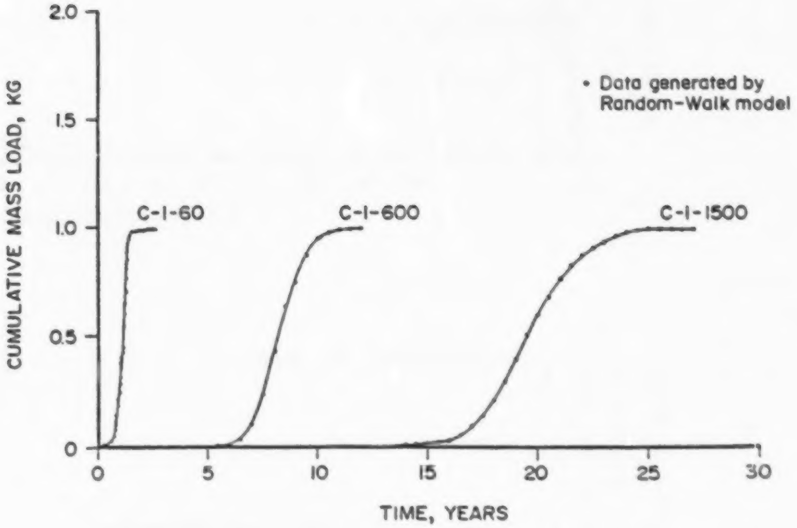
[e] Appearance of contaminants from another model layer attributed to dispersion in a direction against the hydraulic gradient vector

[f] Contaminants enter the lower aquifer beyond a distance of 60 m

[g] Groundwater flow direction in lower aquifer is reversed to cause breakthrough at 60 m exposure point



CONCENTRATION VS. TIME BREAKTHROUGH CURVES FOR 1 KG-1 YR SLUG INPUT WITH SCENARIOS C-1-60, C-1-600 AND C-1-1500



CUMULATIVE MASS LOADING CURVES FOR 1 KG-1 YR SLUG INPUT WITH SCENARIOS C-1-60, C-1-600 AND C-1-1500

Figure B-10. Random-Walk Model Output for Three Scenarios Showing (a) Concentration Breakthrough Curves, and (b) Corresponding Mass-Loading Curves.

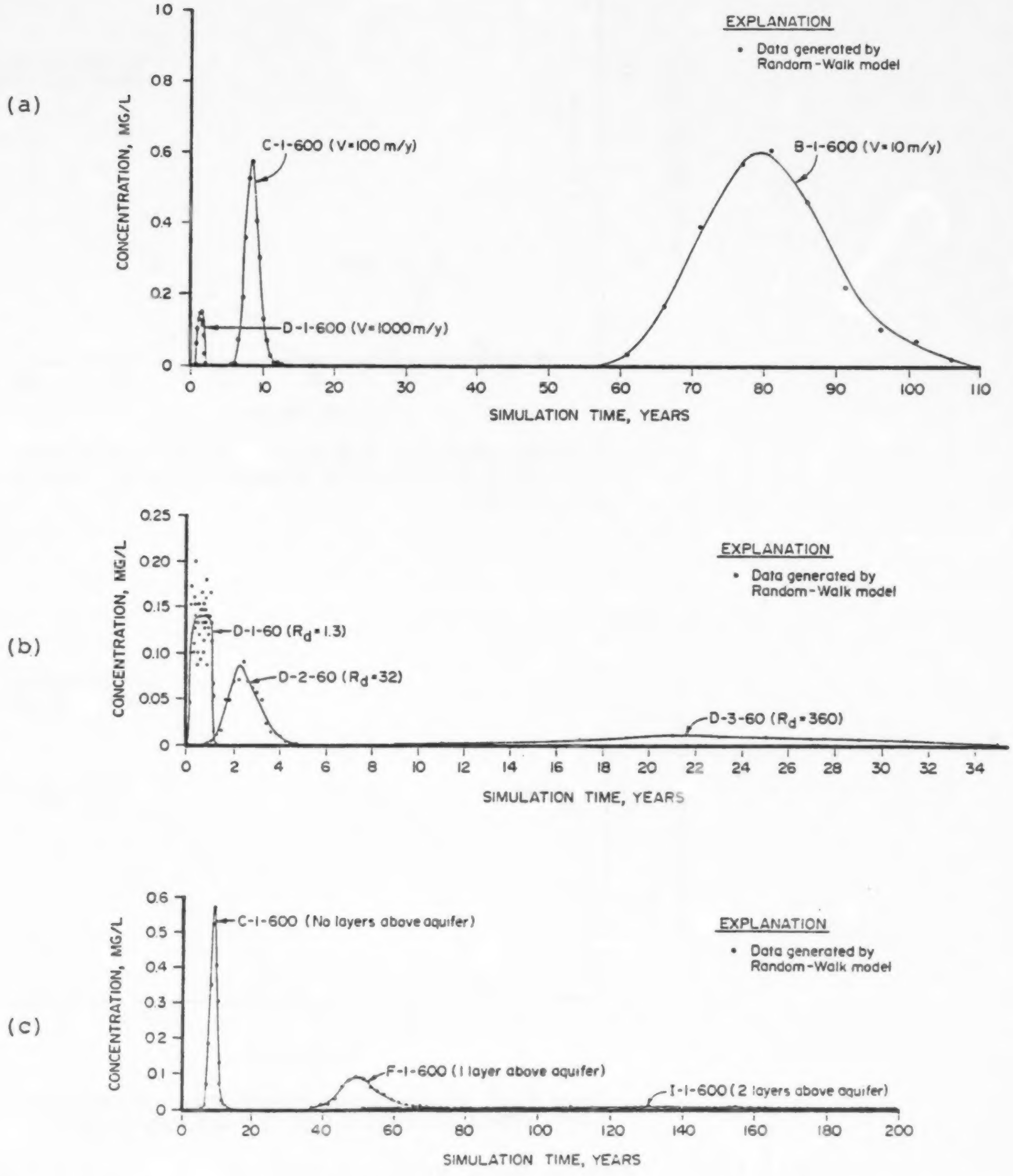


Figure B-11. Three Sets of Standard Breakthrough Curves Showing the (a) Effect of Flow Velocity, (b) Effect of the Retardation Factor, and (c) Effect of Low-Velocity Layers above the Aquifer of Interest.

velocities allow more time for dispersion of contaminants within the flow field, thereby producing a more sustained breakthrough curve. Figure B-11b shows a similar increase in the longevity of the contaminant plume by increasing retardation factors (which decrease contaminant velocities). It is interesting to note that peak concentrations decline with increasing retardation factor values. This would not be the case if the model were simulating a steady contaminant source for a long enough time period so that concentrations become steady with time. Figure B-11c shows a similar pattern to Figure B-11b, in that there is a delay in first arrival, a spreading of the breakthrough curve, and a decrease in peak concentration as low-velocity layers are placed between the source and the aquifer of interest.

3.4.3 Adjusting Output to Fit Site Conditions

The standard breakthrough and mass-loading curves for any scenario can be scaled and added sequentially to fabricate a future scenario at the appropriately matched site-visit facility. These curves can also be adjusted with a time-varying factor that accounts for a decaying source. The scaling of output is based on the fact that concentrations and mass loadings in the aquifer are directly proportional to contaminant concentrations and mass loadings at the source. A scaling factor can easily be determined for each site based on the mass loading rate, and the facility area and dimensions. After the standard curve, or group of curves has been scaled, a future scenario can be developed by following an algorithm for adding the curves together.

The concentration scaling factor must account for the total mass load over a 1-m strip of the facility having a length equal to the length of the hypothetical facility as shown on Figure B-7. In mathematical terms, the expression for adjusting the concentration is as follows:

$$C_s = (L_f M_f / L_s M_s) C_m \quad (5)$$

where,

C_s = Scaled concentration at a hypothetical well (M/L^3)

M_f = Annual mass flux over a 1-m by facility-length source area (M/TL^2)

M_s = Annual mass flux over a_2 1-m by 10-m standard model source area (M/TL^2)

L_f = Length of facility strip area (L)

L_s = Length of model source area (L)

C_m = Concentration at a hypothetical well corresponding to Random-Walk model output (M/L^3)

Expressed this way, the fraction $L_f M_f / L_s M_s$ is the scaling factor. This factor can also be used for adjusting the mass load to the surface-water body by simply replacing the concentrations in Equation 5 with mass loadings.

Figure B-12 is a graphical representation of the process of summing breakthrough curves to simulate a future scenario of contaminant concentrations at an exposure point. Although this figure uses the unadjusted breakthrough curves for scenario C-1-600, it can still represent the summing algorithm for a scaled breakthrough curve.

The standard breakthrough curve for Scenario C-1-600 is generated by a 1-year input of 1 Kg of contaminant mass. To simulate a 10-year scenario with this same standard rate of loading each year, one simply arranges ten

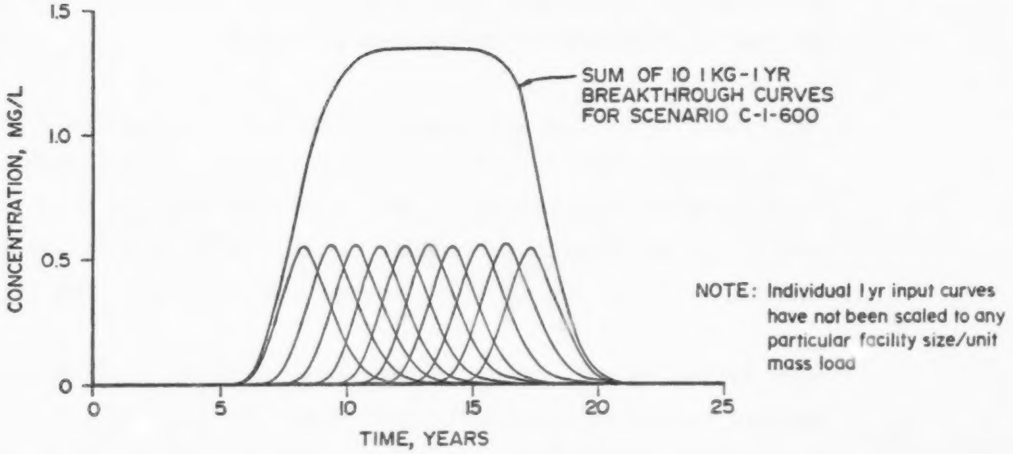


Figure B-12. Graphical Representation of the Method for Summing Individual Breakthrough Curves to Create a Future Scenario.

standard breakthrough curves in sequence and adds the values of concentration from one or more curves that co-exist at any particular point in time to obtain the summation curve. Starting with reference to the first breakthrough curve, each curve begins, peaks, and ends at one-year intervals.

Although this example adds values picked off of continuous curves, it is still possible to apply this general algorithm to data at discrete points in time as computed by the Random-Walk model.

The resulting scaled and summed solution is limited to a single vertical cross section that is centrally located with respect to the facility source and the contaminant plume. The user may question the need for again adjusting the results to account for multiple parallel sections that would encompass the entire facility source and the plume (see Figure B-7).

This factor is not needed for the concentration breakthrough at a well because adding sections will not change the concentration which would be the same in each adjacent section. This is due to the fact that horizontal transverse dispersion is ignored in the model. However, a factor is needed for adjusting the cumulative mass load to a surface-water body, because the total mass load must be accounted for. The mass loading can simply be multiplied by a dimensionless factor equal to the entire width of the facility divided by the unit width of the facility source strip.

4. COMMENT ON MODEL LIMITATIONS

In any transport modeling exercise it is necessary to make simplifying assumptions that limit the ability of the model to accurately predict conditions in the real world. Because the Random-Walk output was used to assess potential health risks, conservative model assumptions were used in this phase of the liner-location project. This approach does not necessarily lead to a set of worst-case scenarios, but it does provide some margin of safety in the assessment of risks.

Model assumptions have been mentioned at appropriate points throughout the text of this appendix. There are seven assumptions that have the greatest effect on computed output and model application. The first five tend to maximize contaminant concentrations and are listed as follows:

1. Locating the exposure points directly downgradient of a source insures that (a) given time, the exposure point will, in fact, become contaminated, (b) the arrival time of contaminants will be minimized, and (c) the concentrations of contaminants will be maximized.

2. Holding thickness constant for any generic distance constrains plume growth vertically and limits dilution of concentrations.

3. The assignment of relatively small dispersivities in the model along with the assumption that transverse dispersion is negligible will tend to maximize concentrations.

4. Ignoring the fact that many water wells produce from more than one layer and that dilution of contaminants will generally take place in a well will tend to maximize concentrations.

5. G&M's assumption that biodegradation is negligible in the unsaturated zone is fair to apply to many contaminants but overestimates concentrations of some constituents.

It is quite possible that the contaminant concentrations could be reduced two or more orders of magnitude if the above assumptions were less conservative. However, it is still not G&M's intent to have output represent the true upper bound because of two other assumptions in the model.

The first critical assumption is that all the earth materials are assumed to be uniform and unfractured--i.e., homogeneous and isotropic (except for dispersivity). The second assumption is that interactions between contaminants that can mobilize less mobile species are considered negligible in G&M's analysis. While increasing heterogeneity can cause more dispersion and reduce concentrations somewhat, a major consequence of these assumptions is that chemical processes that result in a retardation of contaminant movement are assumed to be homogenously distributed throughout the intergranular porous media and are not reduced by fracture flow or chemical interactions.

Groundwater flow through fractures or discrete zones of high permeability and mobilization of hydrophobic organics by miscible organic solvents are examples of processes that were not simulated in this project. These are the types of transport mechanisms that may lead to worst-case scenarios. In these scenarios, computed travel times can be reduced, and peak concentrations can be increased by one order-of-magnitude relative to those computed here.

Without further model studies, it is not possible to determine exactly how the modeled output compares with theoretical extremes. In addition, the site-visit facility data base is not sufficiently well documented to allow definitive statements on the validity of applying theoretical modeling results to these real world situations. It is G&M's best judgment, however, that the generic approach taken here is adequate for evaluating the relative importance of factors affecting liner-location issues.

Apart from the above limiting assumptions, limitations of the modified Random-Walk code itself warrants discussions. As mentioned in this appendix and in the supplemental documentation provided in the separately bound "Random-Walk Model Code and Output for the Liner-Location Project," several changes have been made in the original 1981 code.

Changes include the modeling of particle movement between multiple velocity layers (by G&M) and accounting for the partitioning of the contaminant mass when computing concentrations (two separate methods developed by G&M and T.A. Prickett; personal communication, 1984). While G&M is reasonably confident that the modified code is working correctly, it must point out that it has not been rigorously tested against other validated transport models.

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APPENDIX C

EXPOSURE SUBMODEL

1. INTRODUCTION

The health of individuals living or working near hazardous waste land disposal sites is potentially at risk from releases of wastes from those facilities. Their health can be affected by releases of hazardous wastes to the air, to sources of drinking water, and to surface water and the subsequent consumption of contaminated fish. This appendix presents the approach used by ICF Incorporated to characterize human exposure to potentially contaminated drinking water [illegible] specific land disposal sites in the United States.

Sources of drinking water considered in this appendix are public and private wells and rivers. For each of the sites, data were developed on the number of people using potentially contaminated drinking water from the various sources. Data were also developed on characteristics of drinking water sources. For wells, this included distance from the land disposal facility and well depth. For surface water drinking water sources, we assumed that wastes released from a land disposal facility were transported through groundwater to discharge to a river. Data were obtained on the river's flow rate and distance to any drinking water intake point down river.

Assessment of population exposures to a chemical pollutant includes determining the environmental levels to which the population is exposed. For drinking water wells, those levels are estimated based on the Geraghty & Miller's subsurface transport modeling results described in Appendix B, and on the amount of chemical constituent released. For surface water sources of drinking water, the concentrations of chemicals are estimated based on Geraghty & Miller modeling results, the amount of constituent released, and on a surface water transport model described in this appendix.

In the next section, we describe our methodology. This includes discussing our approach to data collection and assumptions we made to fill data gaps. We conclude with a discussion of our major findings.

2. METHODOLOGY

This section discusses the methods and sources used to obtain information on drinking water supplies and populations served by them in the areas of 70 hazardous waste land disposal sites included in EPA's "site-visit" facility survey. The section is organized as follows:

- Location of hazardous waste land disposal sites
- Drinking water wells and populations served
    - public drinking water wells
    - private drinking water wells
- Surface water sources of drinking water
- Assumptions and limitations

Our findings and conclusions are presented in the final section of this appendix.

2.1 Location of Hazardous Waste Land Disposal Sites

Using latitude and longitude data, the locations of most of the 70 waste sites studied were marked on U.S. Geological Survey topographic maps. These latitude and longitude data were provided by Development Planning and

Research Associates, Inc. (DPRA) from the Hazardous Waste Data Management System. Locations of other sites came from site maps included in the files for the waste sites, addresses of the sites, and in a few cases, local sources. We attempted to verify locations when possible.

With the sites located on the topographic maps, we needed next to identify the direction of ground water flow. The maps were provided to Geraghty & Miller for this purpose. At some sites in regions where irrigation wells are known to exist (e.g., San Joaquin Valley, California) Geraghty & Miller showed flow influenced by wells, if well locations were shown on the USGS maps. In other regions, flow directions were assumed to be unaffected by pumpage and essentially were based on topography and location of the site-visit facility with respect to surface water bodies (including streams, lakes, bays, marshes, and oceans).

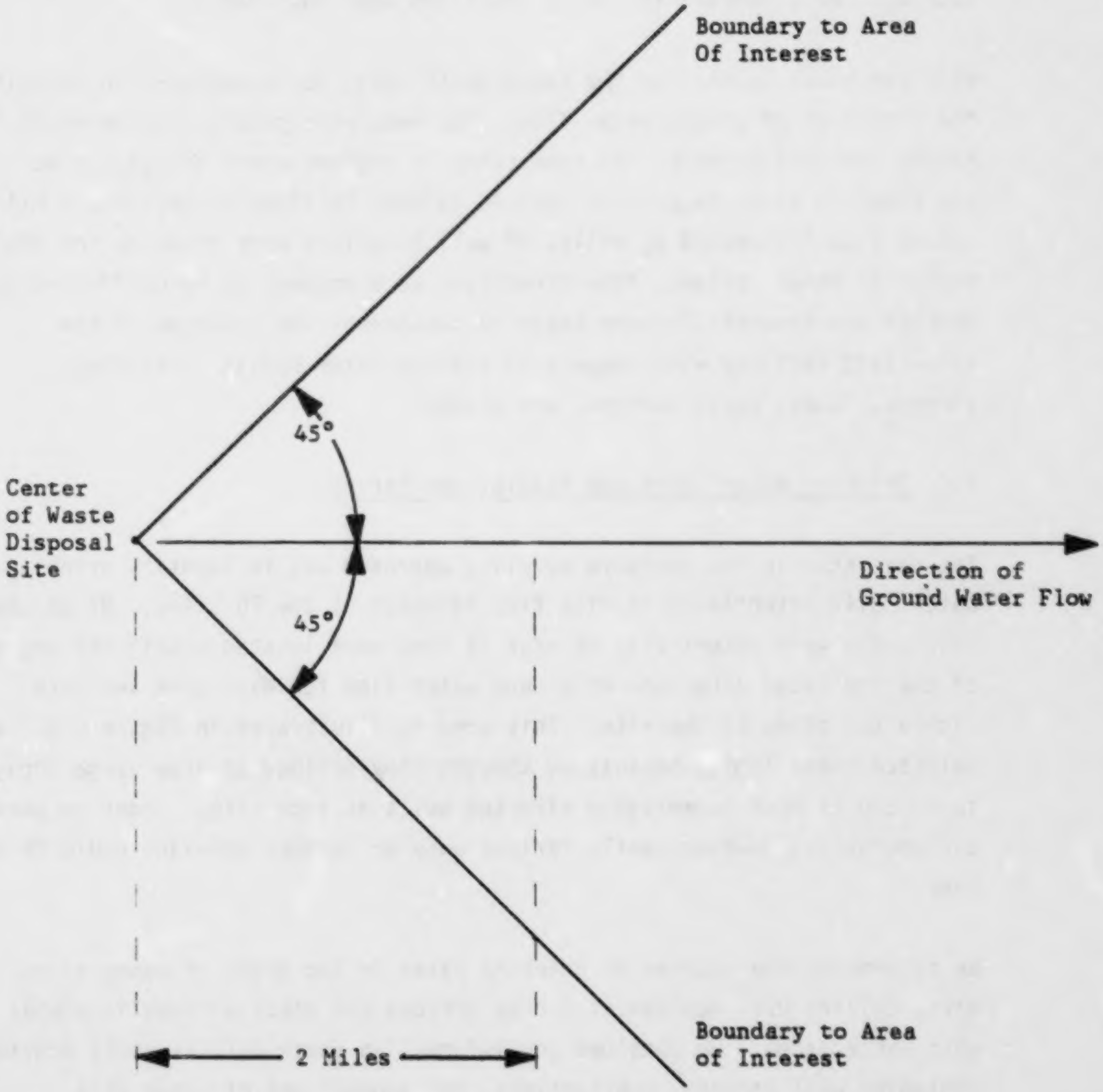
2.2 Drinking Water Wells and Populations Served

The next step in the exposure modeling approach was to identify drinking water wells potentially at risk from releases at the 70 sites. We assumed that wells were potentially at risk if they were located within ±45 degrees of the indicated direction of ground water flow for each site and also within two miles of the site. This area is illustrated in Figure C-1. We selected these limits because we thought they defined an area large enough to encompass most potentially affected wells at each site. Under unusual circumstances, however, wells farther away or farther off-line could be at risk.

We determined the sources of drinking water in the areas of waste sites by first calling U.S. Geological Survey offices and state offices in states with waste sites. We obtained any information these offices could provide, including well records, publications, and suggestions of other data sources. We then called water departments, public works departments, and rural water associations in the waste site areas for further information. Based on information obtained from these sources, we determined the sources of drinking water for the 70 areas.

FIGURE C-1

LOCATION OF WELLS POTENTIALLY AT RISK


Boundary to Area Of Interest
45°
Center of Waste Disposal Site
Direction of Ground Water Flow
45°
Boundary to Area of Interest
2 Miles

We assumed that people living in waste site areas obtained their entire drinking water supply from the public supply serving the area or from private wells if there was no public supply.

2.2.1 Public Drinking Water Wells

We obtained information on public drinking water wells from a number of sources. The computerized drinking water data bases of the U.S. Geological Survey and state agencies proved to be good sources of these data. State agencies also provided us with copies of well records from their files, often with maps showing locations of the wells. Additional information was obtained from the USGS and state agencies by telephone.

Some well information was available from various publications, such as the following:

- A water atlas from Connecticut had maps showing all public wells.
- County reports from counties in Alabama and Texas showed well locations and depths.
- A municipal water supply report from Norman, Oklahoma, had detailed information about public wells.

If well records were not available, we determined the locations of public water supply wells within the area of interest (see Figure C-1) from well records and from local water departments.

We determined the distances of these wells from the waste sites, their depths, and the number of people served. We included wells which were very close to the area of interest among those possibly affected, even if they appeared to be just outside this area. We did this because we believed that the locations of wells and waste sites were not precise enough to exclude wells that were close to the area of interest.

In most cases, the potentially contaminated public wells were part of a larger number of wells supplying drinking water for a given community. We obtained information from local water departments on the number of people served by the water supply. We estimated the fraction of the total water supply provided by the affected wells, assuming that each well contributed equally to the water supply (e.g., one well in a system of 20 wells was assumed to supply one-twentieth of the total water in the system). This information was necessary to allow us to estimate the concentration of chemical constituents in the drinking water (see Appendix G).

Although we obtained pumping rates for the wells in some of the municipal systems concerned, we found that the pumping rates vary depending on the time of day, time of year, and other factors, making it difficult to determine the actual contribution of a single well to the water system. Generally, it was found that, in most cases, the wells do make approximately equal contributions. In addition, we did not have pumping rates for wells in all of the systems affected.

In one case, the affected wells serve a community college. In this case, we estimated that the wells might supply one-tenth of the total water intake for students at the college, because community colleges are generally attended by part-time students who would obtain most of their water elsewhere.

2.2.2 Private Drinking Water Wells

We obtained as many well records as possible of private wells within two miles of waste disposal sites from the sources mentioned previously. Using the locations of the wells given in these records, we determined which were within the area of interest. We included private wells that appeared to be very close to the area of interest among those potentially affected. The well records included the depths of most of the wells.

In areas not served by public water systems, we assumed that people used private wells even if we had no records of such wells. To estimate the number of people using private wells, we obtained population density data for the areas of interest within one-half mile, one mile, and two miles of the waste site. These data were obtained from the Graphical Exposure Modeling System (GEMS) maintained by EPA's Office of Toxic Substances. For each site, estimates were made of the number of people using private wells within one-half miles, between one-half and one miles, and between one and two miles of the waste site and within ±45° of the ground water flow direction. These estimates were made by multiplying the relevant population density value by the size of the area involved.

The manner in which population data are recorded by the Bureau of the Census and reported by GEMS can result in reports of no population for some areas where actually there are people living. This is especially true for small areas. Therefore, in cases where we did not have population density data or where such data indicated zero population but we knew there were private wells, we assumed that each private well served four people. We assumed four as the approximate size of an average household.

We assumed, for modeling purposes, that wells for people within one-half mile of a site were at 1,300 feet from the site; for people between one-half and one mile, we assumed wells at 4,000 feet; and for people between one and two miles, we assumed wells at 8,000 feet. These distances are the approximate midpoints of the three sectors. We used the average of the well depths of all recorded wells within two miles of the waste site (even if they were not in the area of interest) as the depth of these wells. In one case we had no well records and assumed well depths of 100 feet.

In two cases, we had a number of well records, but no population density data. In these cases, we divided the wells into groups of wells at distances corresponding approximately to the distances used with the population data. We calculated an average distance and average depth for each group of wells and estimated the number of people served.

In a few cases, we obtained well records for areas which, according to the population density data, had no people. We assumed in these cases that there were at least a few people living in the area and using the listed wells. In one case a local source informed us that there might be private wells in the area of interest, although population density data indicated that there were no people in the area. In this case, the area was small, and because we had no well information, we assumed there were no wells. In two other cases, we determined that the areas of interest were not served by public water supplies, but we were unable to obtain well records and had no population density data. In these cases as well, the areas were small and we decided to assume there were no wells.

For 13 sites we based a conclusion of no population in the affected area partially on zero population density reported by GEMS. For six of these sites, we had other information on which to base our conclusions. This other information included well records for the general area involved that showed there to be no wells in the affected area and site location information which placed sites very close to surface bodies of water, making it unlikely that wells could exist between the site and the surface water.

Table C-1 presents the types of data used for determining the location and depth of public and private wells and the number of sites for which each type of information was available. For several of the sites, well data of more than one type were used. For 19 of the sites, all data came from local water departments and other local offices. Local sources also provided additional information about the other sites.

TABLE C-1. TYPES OF WELL DATA USED

Type of Data	Number of Sites
Computer Files-Public and Private Wells	23
Well Records-Public and Private Wells	11
Well Records-Public Wells	5
Publications-Public and Private Wells	7
Publications-Public Wells	8
Local Sources Only	19

2.3 Surface Water Sources of Drinking Water

Some communities rely on surface bodies of water 1/ as their source of drinking water. This water could become contaminated by releases from hazardous waste land disposal facilities either by surface runoff or by transport through the unsaturated and saturated zones to discharge to the surface body of water. If this discharge point is within five miles upstream of the drinking water intake location, users of that water are assumed to be potentially at risk. We selected the five mile distance because we thought that this would include most potentially affected drinking water intake points.

Water departments, both municipal and rural, up to five miles downstream from waste sites located near rivers provided information on drinking water sources. For areas served by surface water and for which it appeared that drinking water sources could potentially be affected by the flow of wastes from a waste site, we determined the location of drinking water intakes, the total number of people served by each surface water supply potentially affected, and the fraction of the total water supply provided by the potentially contaminated water.

The Geraghty & Miller subsurface transport modeling results (see Appendix B) provide estimates of the waste constituent mass reaching various distances down gradient from the waste site. These estimates are used to estimate the concentrations of waste constituents in the drinking water obtained downstream from the point where the waste constituents enter the surface body of water.

We assume that all the Geraghty & Miller estimated waste constituent mass enters the surface water and is perfectly mixed throughout the entire volume of water flowing past the discharge point. The annual mass of

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1/ Surface bodies of water include both rivers and lakes. The liner-location model, however, currently does not estimate health risk to users of drinking water obtained from lakes.

constituents entering the surface water is assumed to be diluted in the annual volume of water. The average concentration of waste constituent is estimated by dividing this annual mass by the total annual volume of water, calculated from the average daily flow rate of each potentially contaminated river. This approach assumes no decomposition, precipitation, or volatilization of chemicals. In addition, the effect of drinking water treatment is not considered. We obtained information on surface water flow rates from local U.S. Geological Survey offices, or, in one case, the Army Corps of Engineers.

2.4 Assumptions and Limitations

Several factors that might affect estimates of exposed populations were not taken into account in our approach. The possible movement (both short- and long-term) of people into and out of the area of a waste site was not considered, although such movement would certainly take place. It was assumed that people would live for seventy years in the same area and use the same drinking water source for the whole period. The possibility that people might get a portion of their drinking water at a work site in another location or that people from other areas might drink water from the affected supply was not considered. Movement into and out of an area might increase or decrease the number of people exposed and the total population exposure.

Exposure to waste constituents through eating fish from contaminated water was not considered. Because most of the sites are located near surface water, there might be exposure to contaminated fish in the areas of many waste sites for which no drinking water exposure was found, as well as additional exposures at the sites with affected drinking water. Incorporation of fish consumption into the exposure model would be complicated by the fact that fish caught in one location may be consumed locally or transported and consumed elsewhere. Eating fish caught in waters contaminated with releases from hazardous waste disposal sites may be a significant source of human exposure to waste constituents which bioaccumulate at high levels in fish. However, based on available bioaccumulation data, only a few constituents currently included in the liner-location model have significant bioaccumulation values.

We assumed that the populations in waste site areas would remain constant over the 400 year period considered. We also assumed an even age distribution for the populations studied. We initially assumed that the population in each area would grow at the current growth rate of the United States population as a whole, but this assumption gave extremely high populations at some of the sites after 400 years. The assumption of a constant population might lead to an over-estimate or an under-estimate of the number of people at risk, depending on how the population actually changes with time at a given site.

The approach we took to estimating concentrations of waste constituents in surface bodies of water is based on a very simple transport model and several key assumptions. The key assumptions are that the constituent is perfectly mixed into the surface water body, and that no decomposition, precipitation, or volatilization occurs. Possible treatment of the drinking water is not considered. Some types of treatment might lead to partial or complete removal of some of the chemicals, while chlorination may produce other toxic pollutants. It is therefore difficult to predict the effect of the no-treatment assumption, but it likely would tend to overestimate risk.

In a few cases there was uncertainty about the exact location of the waste sites. A few of the latitudes and longitudes we obtained for the sites proved to be inaccurate. When we were able to check the latitudes and longitudes using site maps or addresses, we did so; in some cases we also checked locations with local sources. It is possible, however, that some waste sites are not accurately located. A small error in location could lead to errors in the ground water flow gradient and in locating possible exposure points. The direction of ground water flow estimated by Geraghty & Miller also is somewhat uncertain.

Population data for some of the sites were not available. In most of these cases we had sufficient information about water supplies so that population data were not essential, i.e., we determined that the areas were served by public water supplies, and it was therefore unnecessary to estimate the population served by private wells. In two cases, because we had no well records, we needed the population density values to determine whether there might be wells. In two other cases, the population data could have improved estimates of exposed population made from well records.

Private well records were not available for some locations and were thought to be incomplete for most locations. Some states do not require the registration of private wells and only have well records which have been submitted voluntarily. Some states which do require the registration of wells do not make the records available to the public, except to people who search the well files themselves. We were cautioned that even when records were available, they were likely to be incomplete. Some well-users might not register their wells; others may be using wells drilled before registration was required. Therefore, there may be unrecorded wells in areas served by public water supplies. Furthermore, the accuracy of the locations, depths, and other information given in records of private wells is generally not checked. More well logs and more accurate well logs would give us better data on well depths and distances from waste sites.

3. FINDINGS AND CONCLUSIONS

Of the 70 waste sites studied, we were able to identify 20 (29 percent of all sites) at which the release of wastes from the facilities potentially would place the surrounding populations at risk of exposure through drinking water. Thirteen of these involve ground water and seven involve surface sources of drinking water. Table C-2 is a summary of ground water exposure data found for the sites while Table C-3 is a summary of surface water exposure data.

TABLE C-2

SUMMARY OF GROUND WATER EXPOSURE DATA

Facility Number	Average Downgradient Distance to Wells (Feet)			Average Well Depth (Feet)			Fraction of Water Supply			Number of People Served		
	1	2	3	1	2	3	1	2	3	1	2	3
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	500	8000	-	248	100	-	.01	1	-	250000	144	-
6	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-
11 b/	1000	6000	-	124	109	-	1	1	-	4	16	-
12 b/	2000	-	-	200	-	-	-	-	-	4	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-
20	300	-	-	250	-	-	.10	c/-	-	1000	c/-	-
21	2200	4000	8000	120	80	80	.10	1	1	15000	51	171
22	-	-	-	-	-	-	-	-	-	-	-	-
23	4000	-	-	100	d/-	-	1	-	-	147	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-
25 b/	1300	2900	-	160	130	-	1	1	-	4	4	-
26	-	-	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-	-	-

---

a/ Private wells are possible - no population density figures or well records were obtained.

b/ Population density figures showed 0 population in area of interest, but well records were obtained, as shown.

c/ Estimated - wells serve a community college.

d/ Estimated - no well records were available.

TABLE C-2

SUMMARY OF GROUND WATER EXPOSURE DATA
(continued)

Facility Number	Average Downgradient Distance to Wells (Feet)			Average Well Depth (Feet)			Fraction of Water Supply			Number of People Served		
	1	2	3	1	2	3	1	2	3	1	2	3
28 e/	5000	10000	-	75	495	-	1	1	-	12	8	-
29	-	-	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-	-	-	-	-
32	5000	-	-	65	-	-	1	-	-	6600	-	-
33 f/	-	-	-	-	-	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-
36	-	-	-	-	-	-	-	-	-	-	-	-
37	-	-	-	-	-	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-	-	-	-	-	-
39	-	-	-	-	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-
41	2500	-	-	95	-	-	1	-	-	20	-	-
42 g/	4400	8200	10000	400	450	250	1	1	1	390	315	180
43	-	-	-	-	-	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-
46	-	-	-	-	-	-	-	-	-	-	-	-
47	-	-	-	-	-	-	-	-	-	-	-	-
48	-	-	-	-	-	-	-	-	-	-	-	-
49	-	-	-	-	-	-	-	-	-	-	-	-
50	8000	8000	-	900	100	-	9	1	-	30000	21	-
51	-	-	-	-	-	-	-	-	-	-	-	-
52	-	-	-	-	-	-	-	-	-	-	-	-
53	3800	-	-	650	-	-	18	-	-	27000	-	-

---

e/ Population density figures were not available; the population and number and location of wells in the area of interest were estimated from private well records for wells in a 2-mile radius of site.

f/ A local source reported private wells in the gradient area, but population density figures show 0 people, and no well records were available.

g/ Data are from public and private well records and the number of connections for the public wells. Four people were assumed per connection. Population density figures were not available.

TABLE C-2

SUMMARY OF GROUND WATER EXPOSURE DATA
(continued)

Facility Number	Average Downgradient Distance to Wells (Feet)			Average Well Depth (Feet)			Fraction of Water Supply			Number of People Served		
	1	2	3	1	2	3	1	2	3	1	2	3
54	-	-	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-
56	-	-	-	-	-	-	-	-	-	-	-	-
57	-	-	-	-	-	-	-	-	-	-	-	-
58	-	-	-	-	-	-	-	-	-	-	-	-
59	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-
61	-	-	-	-	-	-	-	-	-	-	-	-
62	-	-	-	-	-	-	-	-	-	-	-	-
63	-	-	-	-	-	-	-	-	-	-	-	-
64	-	-	-	-	-	-	-	-	-	-	-	-
65 a/	-	-	-	-	-	-	-	-	-	-	-	-
66	-	-	-	-	-	-	-	-	-	-	-	-
67	-	-	-	-	-	-	-	-	-	-	-	-
68	-	-	-	-	-	-	-	-	-	-	-	-
69	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-

TABLE C-3

SUMMARY OF SURFACE WATER EXPOSURE DATA

Facility Number	Downgradient Distance to Surface Water (feet)	Downstream Distance to Surface Water Intake (feet)			Fraction of Water Supply			Number of People Served			Average Annual Surface Water Flow Rate (Cubic feet per Second)
		1	2	3	1	2	3	1	2	3	
1	1700	-	-	-	-	-	-	-	-	-	-
2	2400	5000	-	-	1	-	-	11090	-	-	31376
3	200	-	-	-	-	-	-	-	-	-	-
4	3400	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-
6	50	-	-	-	-	-	-	-	-	-	-
7	4000	-	-	-	-	-	-	-	-	-	-
8	10000	-	-	-	-	-	-	-	-	-	-
9	3300	-	-	-	-	-	-	-	-	-	-
10	50	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-
13	1800	-	-	-	-	-	-	-	-	-	-
14	100	-	-	-	-	-	-	-	-	-	-
15	1600	-	-	-	-	-	-	-	-	-	-
16	1100	-	-	-	-	-	-	-	-	-	-
17	750	-	-	-	-	-	-	-	-	-	-
18	1100	-	-	-	-	-	-	-	-	-	-
19	1300	-	-	-	-	-	-	-	-	-	-
20	5000	-	-	-	-	-	-	-	-	-	-
21	7000	-	-	-	-	-	-	-	-	-	-
22	8000	-	-	-	-	-	-	-	-	-	-
23	800	-	-	-	-	-	-	-	-	-	-
24	5100	-	-	-	-	-	-	-	-	-	-
25	2200	-	-	-	-	-	-	-	-	-	-
26	1100	14100	-	-	1	-	-	1000	-	-	87930
27	1000	-	-	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-	-	-	-
29	3100	-	-	-	-	-	-	-	-	-	-
30	6000	1600	-	-	92	-	-	5500	-	-	217
31	1100	1000	-	-	1	-	-	3900	-	-	a/
32	1400	-	-	-	-	-	-	-	-	-	-
33	2100	-	-	-	-	-	-	-	-	-	-
34	1600	-	-	-	-	-	-	-	-	-	-
35	1600	-	-	-	-	-	-	-	-	-	-
36	2500	2100	-	-	1	-	-	80000	-	-	544300
37	1600	-	-	-	-	-	-	-	-	-	-
38	1700	-	-	-	-	-	-	-	-	-	-

---

a/ No flow rate - surface water is a lake.

TABLE C-3

SUMMARY OF SURFACE WATER EXPOSURE DATA

(continued)

Facility Number	Downgradient Distance to Surface Water (feet)	Downstream Distance to Surface Water Intake (feet)			Fraction of Water Supply			Number of People Served			Average Annual Surface Water Flow Rate (Cubic feet per Second)
		1	2	3	1	2	3	1	2	3	
39	400	-	-	-	-	-	-	-	-	-	-
40	4200	-	-	-	-	-	-	-	-	-	-
41	4600	-	-	-	-	-	-	-	-	-	-
42	1500	-	-	-	-	-	-	-	-	-	-
43	1600	-	-	-	-	-	-	-	-	-	-
44	4600	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-
46	2900	22500	22500	-	.5	.25	-	110000	10500	-	385 b/
47	4000	-	-	-	-	-	-	-	-	-	-
48	400	-	-	-	-	-	-	-	-	-	-
49	5800	-	-	-	-	-	-	-	-	-	-
50	4000	-	-	-	-	-	-	-	-	-	-
51	1900	-	-	-	-	-	-	-	-	-	-
52	13200	-	-	-	-	-	-	-	-	-	-
53	14800	-	-	-	-	-	-	-	-	-	-
54	100	-	-	-	-	-	-	-	-	-	-
55	13200	-	-	-	-	-	-	-	-	-	-
56	500	-	-	-	-	-	-	-	-	-	-
57	1000	-	-	-	-	-	-	-	-	-	-
58	900	-	-	-	-	-	-	-	-	-	-
59	1300	-	-	-	-	-	-	-	-	-	-
60	2900	-	-	-	-	-	-	-	-	-	-
61	3100	-	-	-	-	-	-	-	-	-	-
62	6200	-	-	-	-	-	-	-	-	-	-
63	2000	-	-	-	-	-	-	-	-	-	-
64	-	-	-	-	-	-	-	-	-	-	-
65	200	-	-	-	-	-	-	-	-	-	-
66	6300	-	-	-	-	-	-	-	-	-	-
67	1500	-	-	-	-	-	-	-	-	-	-
68	100	-	-	-	-	-	-	-	-	-	-
69	4000	-	-	-	-	-	-	-	-	-	-
70	3000	100 c/	-	-	.45	-	-	48000	-	-	1108

---

b/ The flow rate shown is for a river which is potenially at risk of being contaminated by releases from the waste disposal facility. The river flows into a lake from which drinking water is taken. The drinking water intake point is near the river.

c/ Intake is known to be close to discharge point, but there is some uncertainty about the exact location. It is possible that intake is a short distance upstream from discharge point.

There are 50 waste sites where it appears that the release of wastes from the facilities would not place people at risk of exposure through drinking water. For 37 of these unaffected sites, water is supplied by sources outside the affected area and for another six sites our findings are based on several different information sources. For five of the unaffected sites, our findings are based primarily on the zero population densities reported for the areas by GEMS. For an additional two sites, we had no information. If all seven of these last two groups of sites actually did have people using wells within the affected area, a total of at most 27 sites (39 percent of all sites) could potentially place local populations at risk through releases to drinking water.

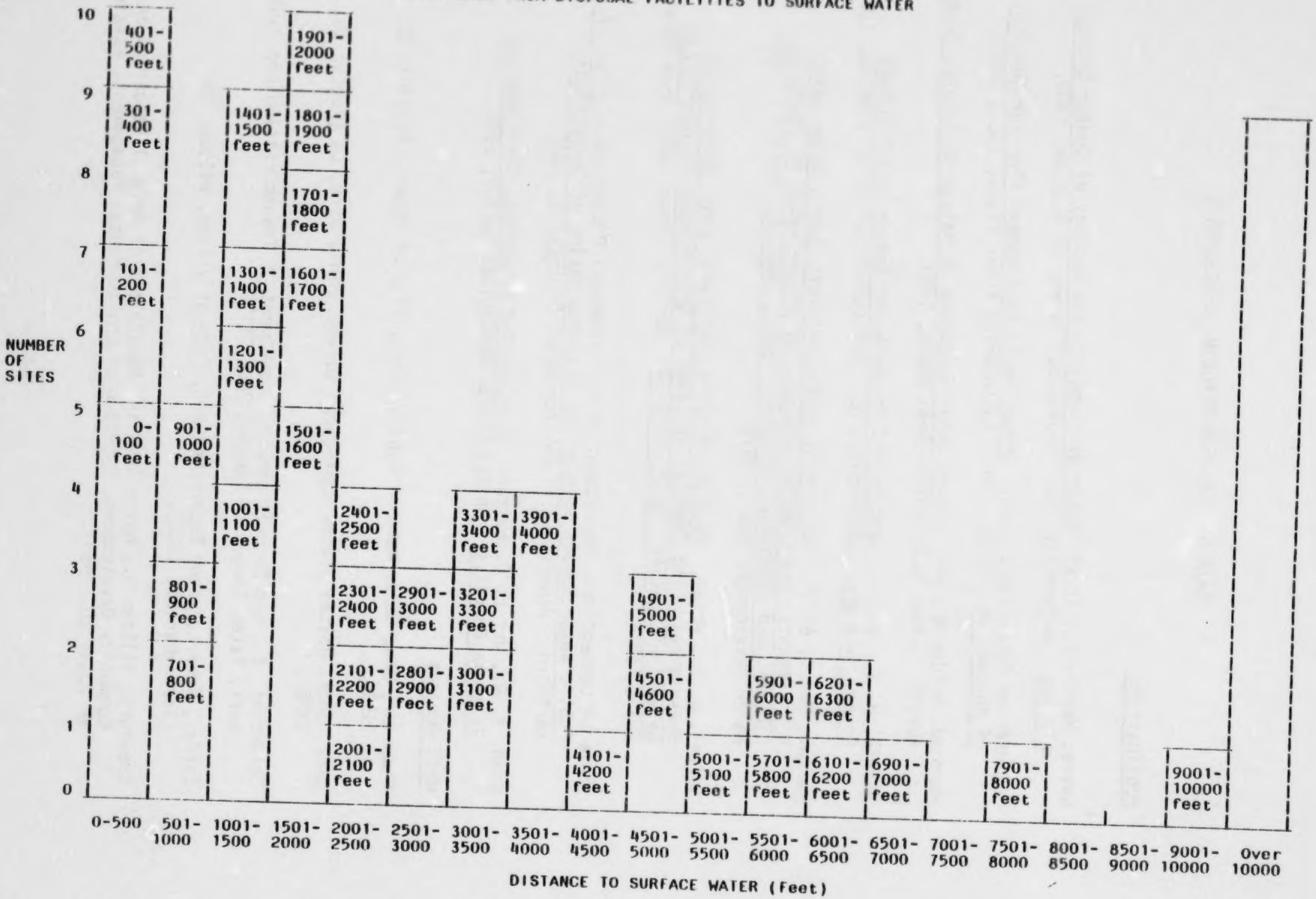
As Table C-2 shows, we found that at the 13 sites (19 percent of the total) with possible ground water exposure, 331,091 people might use drinking water contaminated by releases from the sites. The entire water supply of 8,091 of these people was subject to contamination; the other 323,000 people are served by water supplies which include potentially affected wells supplying from one percent (in the case of a water supply serving 250,000 people) to 90 percent of the total water supply. We found wells at distances of 300 feet to 10,000 feet downgradient from the waste sites; the average well distance was 4,800 feet.

As Table C-3 shows, drinking water came from potentially affected surface water at only seven of the sites. A total of 269,990 people are served by the water supplies in these areas. The total water supply for 95,990 people comes from potentially affected water; the remaining 174,000 people obtain from 25 to 92 percent of their water from potentially contaminated sources.

Most of the 70 sites were found to be located near surface water bodies. As Table C-4 illustrates, 59 of the sites, or 84 percent, are located within 10,000 feet of surface water. Thirty-four sites, or 49 percent, are within 2,000 feet of surface water.

Table 3-4

DISTANCES FROM DISPOSAL FACILITIES TO SURFACE WATER



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APPENDIX D

HAZARD SUBMODEL

1. INTRODUCTION

Risk is the probability of injury, disease, or death over a defined time period. It can be expressed in numerical terms, taking values from 0 (absolute certainty that harm will not occur) to 1 (absolute certainty that it will occur). For some activities, considerable historical data exist on the relationship between an activity and the incidence of adverse outcomes (i.e., the risk). Thus, the risks of death or injury from such activities as driving an automobile or working in a coal mine can be estimated with a fair degree of accuracy from data that have been collected for a number of years.

For some types of chemical exposures, risks can be similarly estimated. Extensive documentation exists on deaths and other types of injuries resulting from accidental poisonings by household products, pesticides, and therapeutic agents, and there is ordinarily little difficulty in estimating the relationship between the extent of use of these substances and the frequency of poisonings. There is generally little difficulty documenting the fact that a given exposure was associated with a given poisoning, although such documentation is usually limited to the short-term effects of a chemical.

The risks associated with other types of chemical exposures -- specifically, those that do not produce immediately observable effects or for which the exposure conditions are highly uncertain -- cannot be so readily assessed. Most of the exposures associated with pollutants released from land disposal facilities are in this category.

This Appendix was prepared by Environ Corporation and ICF Incorporated and describes a methodology for assessing the risks to human health posed by chemicals escaping from hazardous waste land disposal sites. A separate document, Toxicity Profiles for Chemicals in the Liner Location Model, describes the derivation of chemical-specific toxicity parameters required in the methodology. The remainder of the appendix is organized as follows:

- General Methods for Chemical Risk Assessment describes the principles of chemical risk assessment;
- Liner-Location Risk Estimation Methodology describes the procedures used to estimate human health risks and discusses how these procedures relate to traditional assessment methods; and
- Limitations and Uncertainties in Chemical Risk Assessment describes the uncertainties inherent in estimating the risks to humans posed by releases from hazardous waste sites.

Attachment 1 to this Appendix describes the results of an empirical study of dose-response curves of non-carcinogens. This study is the primary basis for the quantitative risk assessment procedures developed and used for non-carcinogens.

2. GENERAL METHODS FOR CHEMICAL RISK ASSESSMENT

The methods used to predict chemical risks, while uncertain, are by no means without a strong foundation in science (NRC, 1980a, 1983). It should be noted that the safe use of thousands of products, including food ingredients, pesticides, drugs and household products, depends upon these methods of risk prediction and their use to establish low risk ("safe") exposures (Food Safety Council, 1980).

A recent study of risk assessment in the federal government conducted by a committee of the National Academy of Sciences describes risk assessment as having four basic components: hazard evaluation, dose-response assessment, exposure assessment, and risk characterization. The content of each of the four steps of risk assessment is described briefly in the following sections.

2.1 Hazard Evaluation

The purpose of hazard evaluation is to provide a critical review of clinical, epidemiological, and experimental toxicity data, and to identify the inherent hazardous properties of a substance, the degree to which the inherent hazards have been identified, and the uncertainties in the available data. A critical feature of the evaluation is a judgment about the appropriateness of inferring human toxicity from animal data. At this stage of the risk assessment, no attempt is made to determine the degree of human risk that might be associated with the substance under evaluation (NRC, 1983).

All chemical substances, whether natural or man-made, have the potential to cause some form of biological injury, disease or death under some conditions of exposure. The terms used to describe this inherent potential is toxicity, and the purpose of the hazard evaluation phase of risk assessment is to collect and evaluate information on the inherent toxic properties of chemicals of interest. Identifying the toxic properties of a substance is not equivalent to identifying its possible risk, and it should not be assumed that because a substance is identified as toxic that it presents a health risk. All of the steps of risk assessment must be completed before any statement can be made about risk.

There are two principal sources of information about the toxic properties of chemical substances: investigations of exposed human populations or individuals (epidemiological or clinical investigations) and experimental studies involving laboratory animals or other biological systems. Knowledge of the molecular architecture of some substances may be of value in predicting some of their toxic properties, but this aspect of toxicological science is still in a very immature stage and cannot be used with confidence without confirmatory experimental data (NRC, 1980a; Klaassen and Doull, 1980).

2.1.1 Studies of Human Exposure

The use of epidemiological or clinical means to investigate the toxic properties of environmental agents would appear to provide data most pertinent for the evaluation of the hazardous properties of substances, because they derive from investigations in exposed human beings. Indeed, well-conducted epidemiological and clinical investigations can provide highly useful information about which our confidence can be high. Epidemiological studies have provided convincing evidence about the cancer-causing properties of agents such as cigarette smoke, asbestos, vinyl chloride, and DES, and about the capacity of thalidomide and DES to cause birth defects. Clinical investigations of exposed individuals have provided immensely important information about the toxicity of a large number of consumer and industrial products (McMahon and Pugh, 1970; Rom, 1983).

There are, however, acknowledged limitations in the use of epidemiological and clinical data for identifying the toxic properties of chemical substances. Some of the more important limitations are as follows:

- For obvious reasons, neither means can be applied to newly-introduced chemicals or to chemicals for which human exposure has been highly limited in the past;
- Accurate data on both the chemical nature of the substance(s) to which populations or individuals may have been exposed and -- more frequently -- on the intensity and duration of their exposure are rarely available, especially when exposures have taken place in the distant past;

- It is difficult to provide proper controls for epidemiological studies, so that strict cause-effect relationships cannot be easily established;

- For investigations of diseases with long latent periods, such as cancer, it is usually difficult to follow exposed persons for periods of time sufficiently long to permit disease to reach a clinically detectable state, so that firm conclusions about the presence or absence of an effect are rarely achievable;

- Epidemiological studies are not generally capable of detecting small but possibly important risks unless the number of people studies is very large (rarely practicable) or the disease uncovered is very rare (e.g., vaginal adenocarcinoma in DES daughters);

- Clinical investigations are usually limited to acute poisonings and cannot provide data on toxic injuries that are not detectable by ordinary clinical means, but which may be important because they can progress to clinical disease; or on the causes of diseases with long latent periods.

Thus, although epidemiological and clinical investigations are immensely important sources of data, their limitations are such that public health officials frequently turn to experimental animal data for information about the toxic properties of chemicals in the environment.

2.1.2 Controlled Laboratory Animal Studies

For studying the toxic properties of chemical substances, experiments involving laboratory animals have a number of advantages over epidemiological and clinical investigations (NRC, 1980b). They can be controlled so that the causal relationship between exposure to a substance and resulting toxicity can be estimated with high certainty. The very important relationship between the intensity and duration of exposure and the magnitude of toxicity can also be established in experimental studies. Using animals, it is possible to investigate a wide variety of toxic effects of chemicals because the animals can be killed and examined in great detail for the presence of various forms of biological injury and pathological changes that cannot be detected clinically. In species such as rats and mice, the effects of lifetime exposures to an agent can be detected in two or three years, the normal lifespan of these species (NRC, 1980b).

These advantages of data from animal studies are partially offset by the obvious fact that animals are not humans. To conclude that an agent can cause certain forms of toxicity in humans because it does so in laboratory animals requires the imposition of assumptions about the biological similarity of various mammalian species. On balance, unless there are human data available that are adequate to refute a specific finding of toxicity in animals, it is reasonable to assume that human toxicity can be inferred from observations in experimental animals. Indeed, this has been a long standing assumption in toxicology and is supported by most of the empirical information available. Animal data have been the principal source of toxicity data for assessing the risks and establishing the safety (or lack thereof) of pesticides, food and color additives, and drinking water contaminants.

2.1.3 Quality and Extent of Data

The quantity and quality of toxicity data available on different substances vary greatly. For some substances (e.g., the recently approved sweetening agent, aspartame), the data base used to make the risk and safety determination can be truly immense, and may include not only the standard toxicity tests described above but also a large number of other studies specific to the substances under evaluation. At the other extreme, the data base for many chemicals may include, at best, only a determination of LD_{50}. For many substances there are no toxicity data at all. For most important industrial chemicals, the quantity and quality of available data fall along a continuum between these extremes.

There is no straightforward way to define the adequacy of a given data base. A chemical is usually tested to determine whether certain of its uses or exposures are safe (e.g., for assessing occupational risks). If the chemical shows up in unintended places (e.g., in ground water), the data base used to assess occupational risk may be inadequate to assess risk associated with the unintended exposure. For example, many agents tested for occupational risk have not been examined for the capacity to cause birth defects because pregnant women are rarely found in certain workplaces. If such a substance shows up in ground water, concern arises about the absence of information on the toxicity of the chemical to the developing fetus. Similarly, the absence of chronic toxicity data on many chemicals is worrisome if they are found to be present in ground water to which people could be chronically exposed. The absence of data does not, of course, mean that a risk exists. Rather, it means that risk (and therefore safety) cannot be ascertained without further studies.

2.2 Dose-Response Assessment

After identifying the types of toxicity associated with a substance, the next step is to describe dose-response relationships. As previously noted, for an exposure of a given duration, the frequency with which toxic effects appear in an exposed population (this is the risk) increases with increasing exposure magnitude (or, dose, which is to be defined). In many cases the types of toxic effects change as exposure increases, becoming more severe with increasing exposure. The dose-response relation is critical to risk assessment, and so must be well-defined. Generally, well-defined dose-response relations for toxic effects are not obtainable from epidemiological studies because of uncertainty regarding the amount of exposure necessary to produce a given response. Therefore, experimental animal data are the primary sources of dose-response information for risk assessment.

It will be useful at this stage to describe more fully the concept of dose. There are various ways in which the dose of a toxic agent can be expressed, but the most common is weight of the agent taken into the body (mg) per unit of the animal's (or human's) body weight (kg) per unit of time (day). Thus, the common units for the expression of dose are mg/kg body weight/day. Dividing intake by body weight is one method to account for the different sizes of various experimental animals and humans (dividing by body surface area is an alternate approach). If a rat ingests 10 mg of a substance, and a human ingests 10 mg of the same substance, the human receives a much lower dose (10 mg divided by the average human body weight of 60 kg yields a dose of 0.17 mg/kg body weight, whereas 10 mg divided by the average rat body weight of 0.25 kg yields a dose of 40 mg/kg body weight).

Dose expressed in this fashion is the means to compare toxic responses among different species -- we say that two species have the same susceptibility to a toxic agent if they show the same response at the same dose (NRC, 1980b; Tomatis, 1977; Calabrese, 1983). It is important to keep this in mind because information about the occurrence of environmental contaminants is usually expressed in units that bear a somewhat complex relation to dose. Such information is useful for risk assessment only after the dose is estimated from it. For example, given a certain level of contaminant in ground water, it is necessary to know how much water is ingested per day to yield an estimate of daily intake (assuming for simplicity that ingestion is the only route of exposure). Daily dose is then calculated by dividing daily intake (mg/day) by average human body weight (generally, 70 kg for adults). This measure of dose is then useful for risk assessment because it is the same measure of dose used in describing the experimental dose-response relation.

A major dose-response issue is that of thresholds. A threshold dose is that which must be exceeded before a toxic effect is produced. The appearance of most toxic effects requires that a threshold be exceeded, although for some effects, notably cancer, there appears to be a biological basis for rejecting the threshold hypothesis. In fact, carcinogenic risk assessment, as currently practiced, generally assumes the absence of thresholds. 1/

2.3 Exposure Assessment

Knowledge of the magnitude and duration of human exposure to environmental agents and, most importantly, the dose that results from this exposure, is another essential component of risk assessment. Exposure assessment is a highly complex subject, which is reviewed here briefly only to emphasize its importance in risk assessment.

Dose is estimated by first identifying the possible routes of contaminant intake. Several possible routes of intake can be identified, including:

- Direct ingestion through drinking water;
- Inhalation of particulates or contaminants that volatize;
- Absorption through the skin during washing and bathing;
- Ingestion through consumption of food derived from plants or animals exposed to contaminants in water or soil; and
- Absorption through the skin during the handling of soil exposed to contaminants.

1/ The subject of thresholds is far too complex for adequate treatment here. Rather than entering more fully into the debate on thresholds, we simply adopt current thinking, at least as applied by the major regulatory and public health agencies (NRC, 1980a, 1983; Klaassen and Doull, 1980; IRLG, 1979).

Only the first two of these intake routes are included in the Liner Location Model.

If the concentrations of contaminants in each of these media (water, food, soil, air) are known, and the extent and frequency of human contact with and intake of these media are known, then the human dose of each of the contaminants can be estimated. In most cases, dose estimation is relatively uncertain because of uncertainties in knowledge of concentrations, and the magnitude and frequency of human contact with and intake of the various media. It has become the practice to adopt certain average values for contact with and intake of certain media (e.g., for adults, 2 liters of water consumption per day) and, if this is done and approximates reality, then reasonably accurate estimates of dose can be made (Nisbet, 1981; Cralley and Cralley, 1979).

An additional factor that influences dose is absorption. Substances that are ingested have to pass through the gastrointestinal wall, and substances coming into contact with the skin or lungs have to pass through these barriers to be effective. [1] Not all substances pass through these barriers at the same rate and information about absorption rates is needed to make estimates of internal dose. Such data are frequently not available, and cannot be obtained without experimental studies in humans, so again it has become the practice either to adopt absorption rate values from studies of compounds having similar chemical and physical characteristics or to assume that absorption is complete by all routes (Nisbet, 1981). For the Liner Location Model, complete absorption is assumed for all chemicals by all routes.

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[1] We note that some substances produce toxicity directly at the point of contact (skin, lung, gastrointestinal tract). Absorption is necessary if effects are to be produced at internal body sites (systemic effects).

2.4 Risk Characterization

2.4.1 Non-Carcinogens

No methods are commonly used to make explicit low dose risk estimates for non-carcinogens. Such methods are required for the model and had to be developed. These methods are fully described in Section 3. In this section, we describe the traditional methods of risk characterization for non-carcinogens.

It has been the practice to divide the experimentally-determined no-effect level (NOEL) by a large "safety factor" to estimate acceptable human doses of substances that produce forms of toxicity other than carcinogenicity. This practice had its origins in the 1940s and 1950s, in connection with food additive and pesticide regulation, and has been extended to other areas such as drinking water contaminants (NRC, 1980a, 1983). It is based on the notion that there is likely to be a much wider range of susceptibilities in the human population than there is in the test animal group from which the NOEL is obtained. The human population is genetically far more diverse than laboratory animals and contains certain subgroups of individuals (infants, the ill) that are likely to be more susceptible than the test animals. Moreover, the human population is exposed to a very wide range of other environmental agents, and includes people who smoke, drink alcoholic beverages, and take medicines. Such additional exposures pose a higher background of risk on the human population than that experienced by test animals, and it has been assumed that this additional burden may generally increase the susceptibility of the human population over that of test animals. It is also likely that the variation in threshold doses for a particular substance is much wider in the human population than in a small, genetically homogeneous animal group (NRC, 1983).

For these reasons, it has been proposed that the threshold dose for the human population is likely to be lower than that approximated by the experimental NOEL. To take into account all of the uncertainties about the relative susceptibilities of the human and animal populations, and also the wide range of susceptibilities within the human population, the experimental NOEL is divided by a safety factor to yield an "acceptable daily intake" (ADI) for humans. If the NOEL derives from a well-conducted chronic toxicity study, and has been carefully identified, the usual safety factor is 100 (FDA, 1982a). If NOELs are available from studies in several animal species, the value for the most sensitive species (the lowest value of NOEL) is ordinarily chosen.

Risk characterization for non-carcinogens traditionally takes the form of determining the margin-of-safety (MOS), which is the numerical value derived when the experimental NOEL is divided by the projected or measured human dose. A judgment is then needed to determine whether the MOS is sufficiently large to protect most members of the exposed population. Guidance on the adequacy of a given MOS can be obtained by comparing the commonly used safety factors for establishing ADIs to the MOS; for chronic toxicity, an MOS of 100 might be considered adequate, assuming the data are fully accurate (NRC, 1980a; 1983).

2.4.2 Carcinogens

If a unit risk value (risk per unit dose) is available for a carcinogen, this value is multiplied by the actual daily lifetime dose experienced by an individual to derive an estimate of risk. In this case, an explicit risk is estimated, and takes values between 0 and 1. Even for well-studies carcinogens, this estimate of risk is uncertain, and it cannot be claimed to be the true risk. EPA and FDA use "upper bound" estimates of risk, with the true risk being less than that estimated by their procedures. The agencies give no information about the likely magnitude of the difference between the upper bound and the true risk (NRC, 1983; IRLG, 1979; Rodricks and Taylor 1983; USEPA, 1976; FDA, 1982b). In any case, it has become common practice to use the numerical estimates of risk as decision-making tools for separating significant from insignificant risks 1/ (see NRC (1983) and Rodricks and Taylor (1983) for full discussions of this point).

1/ An insignificant risk is one that is so low that there is no public health benefit to be gained by further risk reduction (FDA, 1977).

This section has reviewed the general principles of chemical risk assessment. In the next section we describe the specific risk assessment methodology used in the liner-location project.

3. LINER-LOCATION RISK ESTIMATION METHODOLOGY

This section presents the risk estimation equations used in the Liner Location Risk and Cost Analysis Model. It also describes in detail the principles and procedures for determining the chemical-specific values required as inputs to the equations. The methods discussed here correspond to the hazard evaluation, dose-response assessment, and risk characterization components of risk assessment, as defined in Section 2. The remaining component, exposure assessment, is not covered here, but is described in Appendices A, B, C, and G. This appendix is limited to the methods of estimating the risks of a given chemical dose.

The Liner Location Model risk equation estimates the probability of chronic toxic response as a function of the lifetime dose of the chemical producing the response. The model predicts explicit probabilistic risks for both carcinogens and other chronic toxicants. For carcinogens, the model predicts a finite toxic response at all doses -- i.e., it is a non-threshold model. This is consistent with traditional EPA risk assessment procedures for carcinogens. For non-carcinogens the model predicts zero risk for all doses less than the human minimum effective dose (MED) divided by 100. This, in effect, introduces a population threshold two orders-of-magnitude below the human MED. For non-carcinogens, such a model differs from the traditional approach insofar as the model predicts finite risk values at dose levels above the population threshold.

Traditional methods for non-carcinogens have, with few exceptions, avoided confronting the central question addressed by this model: what is the probability that a given chemical will produce a response at doses outside of (ordinarily below) the range of doses for which data are available? If the decision process is to take account of non-carcinogenic risk (defined as the probability of an adverse effect), then a usable model must incorporate a measure of risk in the exposure region of interest.

The traditional methods for incorporating toxicity data into the regulatory process were the only ones available at the time the present methodology was developed. The available methods for carcinogens could be directly adopted for carcinogenic components of hazardous wastes because they are designed specifically for use in the type of risk analysis model envisioned. For substances exhibiting other forms of toxicity, the traditional scheme was clearly unsuitable (the model would not be assisted by schemes that simply defined "acceptable intake" and left no room to consider the dependence of risk upon exposure). The methodology developed and applied for non-carcinogens is similar to that used in the RCRA Risk-Cost Analysis Model (ICF, 1984) but is otherwise without precedent. For this reason, we have provided extensive discussion at the appropriate place in the presentation of the risk methodology of the nature and basis for the risk model used to provide risk values. We have also included the empirical study on which the methodology for non-carcinogens is based as Attachment 1 to this Appendix.

A special case of threshold toxicity is adverse effects on embryo development (teratogenesis, embryotoxicity). The risk model treats this effect differently than other threshold effects. Effects on embryo development result from short-term exposures, not lifetime exposures. Therefore, using lifetime chemical doses to estimate risk of this type of toxicity is inappropriate. The risk estimation model uses yearly (smallest time increment in the Model) doses to estimate these risks. The same risk equation is used except that annual dose is substituted for lifetime dose. Because effects on embryo development can possibly result from very short-term (i.e., days) peak exposures, occurrence of these effects may be underestimated by the model.

The remainder of Section 3 is organized as follows:

- Chronic Risk Estimation Model - The basic risk estimation equation is presented.
- Principles for Assessing Inherent Hazard of a Chemical - The major sources of uncertainty and the assumptions used to address them are discussed for the important parameters of the risk estimation model.
- Procedures Used for Assessing Inherent Hazard of a Chemical - The specific methods used to assign values to the parameters in the risk estimation model are described.

3.1 Chronic Risk Estimation Model

In the chronic risk estimation model, a chemical's inherent hazard is defined in terms of three parameters. The first is the probability of harm, or risk, per unit dose of a chemical (H). The second is the shape factor, K, which specifies the shape of the dose-response curve. The third is a scaling factor, S, which scales the risk estimates for non-carcinogens. Taken together, these three factors describe the toxicity, or inherent hazard, of a chemical constituent. The procedures used to derive these factors for specific chemicals are given in Section 3.3. The three inherent toxicity factors are combined with the measure of human exposure, total lifetime dose (D), to yield risk. The dose is based on chemical release and transport predictions and is estimated by other parts of the Liner Location Model. The equation combining the inherent toxicity factors and dose to give risk is:

$$\text{Risk} = [H] \times [S] \times [D]^{K}$$

This equation estimates risk to an individual. Population risks are then estimated by multiplying individual risk by the number of people exposed.

3.2 Principles for Assessing Inherent Hazard of a Chemical

The chronic model incorporates, with some modifications, traditional methods for addressing uncertainties associated with the inherent toxicity of chemicals. This section describes four principal sources of uncertainty and the simplifying assumptions used in the model to deal with them.

3.2.1 Interspecies Differences

It is a widely accepted principle of toxicology that, with certain exceptions, data on the toxicity of chemicals in animals can be extrapolated to humans to predict likely adverse effects. However, it is also a truism that humans are not simply big rats. In addition to the obvious differences in size and lifespan, there are interspecies differences in physiology, metabolism, and pharmacokinetics that can influence susceptibility to some toxic effects. For example, differences in the structure of the placenta in different mammals may alter the embryotoxic or teratogenic efficacy of some chemicals, and quantitative and qualitative differences in metabolism can affect the rate of excretion of a toxicant or the amount of an active metabolite present. Absent data on such factors, we have adopted the traditional principle that humans and test animals respond similarly to toxic chemicals. For non-carcinogens, we assume humans and test animals are at equal risk at the same dose in mg/kg body weight/day. For carcinogens, we follow the more conservative approach adopted by EPA's Carcinogen Assessment Group of assuming equal risk for the same dose in mg/m^2 body surface area/day.

3.2.2 Influence of Route of Exposure

In cases when the main toxic effect of a chemical occurs at places distant from where it enters the body, it is reasonable to use data derived from one route of exposure to assess toxicity from exposure through a different route. For example, toxicity data on a chemical that causes liver damage upon inhalation may be used to assess hazards not only by inhalation but also by dermal absorption. For chemicals that cause their toxic effects only at the site of entry to the body, such conversions are not appropriate. For example, data on a substance that causes damage only to the upper respiratory tract when inhaled at high concentrations are not used to predict the effects of ingestion at low concentrations. We make this distinction of toxic endpoint by route of exposure for several chemicals in the Liner Location Model (e.g., chromium is considered a carcinogen by inhalation and a chronic liver and kidney toxicant by ingestion). In the absence of data on most chemicals, we conservatively assume 100 percent absorption of chemicals by all routes of exposure.

3.2.3 Effects of Different Lengths of Exposure

The chronic risk model characterizes only potential long-term adverse effects of low-level exposures. Hence, the most useful type of data for assessing toxicity comes from chronic studies (studies that cover a large portion of the subject's lifespan, whether animal or human). Where data from chronic studies are not available for a particular chemical, it may be possible to use data from subchronic studies (generally animal studies of one to six months duration). Subchronic studies cannot be used to quantitatively assess carcinogenic risks, however. Subchronic studies are less sensitive than chronic studies because of the shorter exposure period and shorter time allowed for development of progressive adverse effects, a point that must be considered when comparing the inherent hazards of two chemicals if only subchronic data are available for one of them. Our approach to this problem is the traditional one of adjusting the subchronic dose-response data by a factor corresponding to the difference in sensitivity of subchronic and chronic studies, generally two- to five-fold.

3.2.4 Dose-Response Curves

Responses to hazardous chemicals may be classified as "dichotomous" if an individual either does or does not respond (death, cancer, birth defects), or "graded" if the response is measured on a continuous scale (organ weight, enzyme activity), or a combination of the two. In the case of many carcinogens there is some evidence, largely theoretical, that risk declines monotonically with dose, reaching zero only at zero dose, i.e., with no threshold. Further, it is widely accepted that for most carcinogens risk is linearly related to dose at low doses. The low-dose risk extrapolation model currently used by EPA for carcinogens (the linearized multi-stage model) incorporates these assumptions, at least for the upper confidence limit on risk. For most types of non-carcinogenic effects, the incidence, or more commonly the severity, of the effect declines with dose until a threshold is reached at a dose greater than zero. Below the threshold, no adverse effect is thought to occur. The position of this threshold is, however, likely to vary to some extent due to variation in individual susceptibility.

As mentioned above, one measure of toxicity is the probability of harm at a particular dose (H). In the case of effects believed to display thresholds, the "probability of harm" may be considered to be the probability that an individual's threshold for that effect is exceeded at a particular dose. Unlike the probability of cancer, it is unlikely that the probability of exceeding an individual's threshold will be a linear function of dose. Unfortunately, how this probability varies with dose has not been widely considered in the scientific community. Indeed, traditional means for using toxicologic data on threshold-type effects have been to identify an experimental "threshold" or "no observed effect level," and then to apply a "safety" factor to define a dose below this level at which the probability of harm is considered to be zero, or at least insignificantly small. That this traditional approach has generally served its intended purpose well, and that the "safety factors" used are relatively small, would imply that the probability of harm falls more rapidly with decreasing dose than a linear function would. The risk estimation equation used in the Model allows the incorporation of a non-linear dose-response function to account for this rapid decrease.

3.3 Procedures Used for Assessing Inherent Hazard of a Chemical

Against the background given in Section 3.2, we present the inherent hazard assessment procedure applied to each chemical. Recall that risk is given by the following simple relation:

$$R = [H] \times [S] \times [D]^K$$

Recall also that in this model, a chemical's inherent hazard is defined by the values for H, S, and K. For reasons to be explained, K is chosen as 1 for carcinogens and as 2 for all other types of toxic substances (except for lead, copper and fluoride when a value of 4 is used). Further, S is set at 1 for all carcinogens. The basic risk estimation equation can thus be simplified to:

$$R_{car} = [H] \times [D] \quad \text{(carcinogens)}$$

or

$$R_{other} = [H] \times [S] \times [D]^2 \quad \text{(other agents, except lead, copper, fluoride)}$$

The risk equation for non-carcinogens predicts no absolute threshold (i.e., Risk = 0 only at zero dose). Although this fact may at first appear to diverge from the traditional assumptions of toxicology, we note that under the non-linear model of dose-response assumed here, risk declines relatively quickly below the experimental dose range. Further, to make this model more consistent with traditional risk assessment procedures, all risks corresponding to doses less than two orders-of magnitude below the human MED were set to zero (mathematically, the risk equation is discontinuous for non-carcinogens, with risk going to zero for all values of $D < \frac{MED}{100}$.

3.3.1 Derivation of H

The key feature of the assessment scheme is the definition of the dose-response factor, H, as the probability of response per unit dose. For carcinogenic chemicals, this definition of H coincides exactly with the definition of "unit risk" used by EPA. The widely adopted assumption is that dose-response relationships for carcinogenic effects are likely to be linear and nonthreshold at low doses. Thus, the slope of the dose-response relationship is independent of dose and is defined as the unit risk. These relationships are based primarily on animal data, although linear dose-response relationships can also be fitted to human data. For carcinogenic chemicals, we have set H equal to unit risk values derived by EPA (using the linearized multistage model), where they are available. In other cases, unit risks (i.e., H) were estimated by a simple approximation using the one-hit model. In keeping with traditional EPA practice, unit carcinogenic risks used here incorporate the assumption that humans and test animals are at equal risk at the same dose per surface area (mg/m^2 surface area/day). We also note that these values are the upper 95% confidence limits of the unit risk; therefore, all carcinogenic risk estimates calculated by the Liner Location Model are upper bound estimates.

For non-carcinogens, H is derived from the observed (experimental) dose-response data by assuming that in the region close to and below the low end of the dose-response curve, response declines as dose to the Kth power:

$$R = [H] \times [D]^K$$

A value for H for a specific chemical can be derived from the quantitative relationship between the MED, the minimum effective dose, and Ro, the observed response at the MED. Thus,

$$H = Ro/[MED]^K$$

This equation was used to estimate H for non-carcinogens in the Liner Location data base. The estimated H value can then be used to estimate human, non-cancer risks for various values of D.

Derivation of H for non-carcinogens requires further discussion. Because there are no sources similar to EPA's collection of unit risk values for carcinogens, H values for non-carcinogens must be derived from experimental toxicity data. The critical experimental values needed to derive H are MED and Ro. These two experimental factors have somewhat different meanings for dichotomous and graded responses. Note that the concern in both cases is for chronic toxicity.

For dichotomous responses, observed responses are recorded as the fraction of the experimental population affected at a given dose. Typically, the MED is the dose that produces about a 10 percent increase in the incidence of adverse effects. For such responses, the MED and corresponding Ro can be selected from the experimental data; H is then simply calculated as $Ro/(MED)^K$. The units of H are $(mg/kg/day)^{-K}$. If Ro is not presented in the experimental data, we assume it is 0.1 (10 percent).

For graded effects, such as liver enlargement and body weight depression, the MED may be the dose at which all subjects in the experimental population are minimally affected, rather than the dose at which a minimal number of subjects are affected. In many cases, toxicity data are reported only as group averages, so that it is not possible to determine the incidence of effects. Therefore, unless the data indicated otherwise, we assumed that for graded effects, all members of an exposed population would be minimally affected at the MED. Immediately below the MED, the fraction of the population whose individual thresholds are exceeded declines as D^K. Calculation of H for such a response is performed by assuming, unless the data show otherwise, that Ro = 1.0 at the MED.

Finally, some provision must be made for the fact that for many chemicals, the available toxicity data do not reveal a chronic MED. Several types of limitations are common, including:

- Chronic toxicity data may be available but the lowest dose observed to cause toxicity may not be the MED; and

- No toxicity data reflecting the effects of chronic exposure may be available; rather, subchronic data, reflecting the effects of partial lifetime exposures, may be the only data available.

We have encountered numerous examples of these types of data limitations. Table D-1 lists the decision rules used to derive chronic MEDs from limited data. These rules are based on practices long used in toxicology (McNamara, 1976).

3.3.2 Derivation of K

As stated before, K was set to 1 for carcinogens and 2 for non-carcinogens, with a few exceptions. Setting K=1 for carcinogens results in a linear, low-dose risk model consistent with current EPA practice. Setting K=2 for non-carcinogens results in a quadratic risk model, an innovative approach based primarily on an empirical study of dose-response curves of non-carcinogens. This study report is included as Attachment 1 to this Appendix and summarized below.

We evaluated dose-response curves for chemicals with various non-carcinogenic effects. We collected the dose-response data for these chemicals from the primary literature, and Science Research Systems, Inc. subjected them to statistical analysis. The results of this analysis must still be considered preliminary because the number of data sets analyzed, while relatively large, is still too small to provide a basis for strong generalizations.

Data for teratogenic and reproductive toxicity were analyzed, as were data for a variety of other toxic effects. The dose-response data were analyzed statistically to determine the range of values of K that is compatible with non-carcinogenic dose-response data. The analysis revealed that is is appropriate to use values of K greater than 1 for the effects studied.

Table D-1

RULES FOR DERIVING CHRONIC MEDs FROM LIMITED DATA

Rule 1:	To derive a chronic MED from a subchronic MED, divide the subchronic MED by 5 (i.e., chronic MED = subchronic MED/5) a/ In the special case where the effect occurring at the lowest dose level is a teratogenic or fetotoxic effect, this adjustment procedure is not appropriate and no adjustment is made because such effects depend on treatment occurring during a specific short period (gestation).
Rule 2:	To derive a chronic MED from an effective dose presumably higher than the MED, scientific judgment is used. If the effects reported are of minimal degree or incidence, no adjustment is made. If the effects seen are of moderate or severe degree, or greater than about 10% incidence (above control incidence), the experimental dose is divided by 5 to estimate the MED.

a/ McNamara examined 74 sets of data on no-effect levels in subchronic and chronic studies. In about half of the cases, the difference in sensitivity was two-fold or less, and in about 95% of the cases the difference was five-fold or less (McNamara, 1976).

The median values for K computed under various classifications of data were similar, ranging from 1.70 for teratogenic effects to 2.26 for non-reproductive forms of toxicity. The median value of K for the combined data sets was 1.74.

Although they were not examined in this study, many carcinogenesis data sets probably exhibit values of K greater than 1. The assumption of K = 1 for the low dose region is retained for carcinogens for theoretical reasons. The major theoretical reason is based on the existence of a background incidence of tumors to which additional carcinogenic insults simply add (Crump, et al., 1976). Hoel (1980) demonstrated that if any of this background is additive (i.e., occurs by the same mechanism as the added carcinogen), low dose linearity will occur. Assuming there are no theoretical bases for considering non-carcinogenic dose-response curves to be linear in the low-dose region (and we know of none), the median K value determined in this study could be said to apply in the low dose region.

With three exceptions, we have adopted K = 2 as a sufficiently close approximation to the observed median value of 1.74 for purposes of the present model. We have assigned a value of K = 4 for lead, copper, and fluoride because there are sufficient data on the health effects of these substances in humans to be much more certain than is possible for other substances that the risk to humans becomes extremely small at doses not far below the MED. The choice of K = 4 ensures that the predicted risks for lead, copper, and fluoride exposures will not grossly overestimate the true risk at doses below the MED.

3.3.3 Derivation of S

A linear scaling factor, S, is used in the risk equation risk estimates for graded effects. The scaling factor is included to compensate for the conservative assumption made during the derivation of H that the MED for graded effects corresponds to an incidence of 1.0 (100 percent). This assumption was necessary to "dichotomize" toxicity data for graded effects so that all risks could be estimated in the same units. We believe that risk estimates based on this assumption are overly conservative; therefore, a scaling factor, S, was incorporated in the model.

For carcinogens, S is always equal to 1 because H values for these chemicals are based on quantal effects. For most other chemicals in the data base, S was assigned an arbitrary value of either 0.1 or 0.5 and used to scale the risk estimates. The assignment of 0.1 or 0.5 was based on the relative severity of the toxic effect(s) at the MED. Chemicals for which the H value was derived from relatively minor effects (e.g., changes in blood enzyme levels, body weights) were assigned an S value of 0.1; other chemicals we assigned a higher value of 0.5, because it was considered less acceptable to possibly underestimate risks for more serious effects (i.e., the approach is more conservative for more serious effects).

The appropriateness of the scaling factor is currently being evaluated and alternate approaches to reducing the conservatism of risk estimates for chemicals causing graded effects are being assessed. The possibility of developing and incorporating an optional scaling factor to account for the differing severity of effects is also being studied.

Table D-2 summarizes the toxicity data for the waste constituents currently in the Liner Location data base. Values for H, S, and K and the nature of the toxic effect at the MED are presented. The values of H are documented in a series of toxicity profiles we have developed under separate cover for each chemical. The profiles present the critical studies and the MED and Ro values upon which the H value is based.

3.3.4 Data Sources

We evaluated the inherent hazard factors for waste constituents by first reviewing secondary sources to determine the lowest exposure level associated with toxic effects. Some of the principal secondary sources were the monograph series of the International Agency for Research on Cancer (IARC), the National Academy of Sciences (NAS) series Drinking Water and Health and Medical and Biologic Effects of Environmental Pollutants, NIOSH Criteria Documents, Casarett and Doull's Toxicology, and EPA's Ambient Water Quality Criteria Documents. In addition to these secondary sources, we consulted carcinogenesis bioassays of the National Cancer Institute (NCI).

TABLE D-2

TOXICITY PARAMETERS

CONSTITUENT	UNIT RISK (H)	SCALING FACTOR (S)	SHAPE FACTOR (K)	TYPE OF EFFECT
ACENAPHTHENE	0.1150E+02	1.0	1	CANCER
ACETALDEHYDE	0.1590E-03	0.5	2	TRACHEA
ACETONE	0.8000E-05	0.5	2	STOMACH
ACETONITRILE	0.3600E-01	0.5	2	MULT ORG
ACROLEIN	0.6600E+00	0.5	2	BLOOD
ACRYLONITRILE	0.2400E+00	1.0	1	CANCER
ALDICARB	0.1000E+02	1.0	2	MORTALITY
ALLYL ALCOHOL	0.6270E+01	0.5	2	KID&LIV
ANILINE	0.1900E-01	1.0	1	CANCER
ANTIMONY	0.1800E-03	0.5	2	HEART
ARSENIC	0.1500E+02	1.0	1	CANCER
BARIUM	0.3000E+00	0.5	2	TRACHEA
BCME	0.9300E+04	1.0	1	CANCER
BENZ(A)ANTHRACENE	0.1150E+02	1.0	1	CANCER
BENZ(A)PYRENE	0.1150E+02	1.0	1	CANCER
BENZENE	0.5200E-01	1.0	1	CANCER
BENZOTRICHLORIDE	0.1210E+02	0.5	2	MULT ORG
BENZYL CHLORIDE	0.1800E-01	0.5	2	RESPIRAT
CADMIUM	0.7800E+01	1.0	1	CANCER
CARBON DISULFIDE	0.5300E-01	1.0	2	EMBRYO
CARBON TETRACHLORID	0.1300E+00	1.0	1	CANCER
CHLORDANE	0.1610E+01	1.0	1	CANCER
CHLOROACETALDEHYDE	0.3760E+02	0.5	2	BLD&LNGS
CHLOROBENZENE	0.2360E-02	0.5	2	KID&LIV
CHLOROFORM	0.7000E-01	1.0	1	CANCER
2-CHLOROPHENOL	0.1000E-01	0.5	2	KIDNEY
CHROMIUM VI	0.2000E-01	0.5	2	KID&LIV
CHRYSENE	0.1150E+02	1.0	1	CANCER
COPPER	0.2560E+02	0.5	4	BLOOD
CYANIDES	0.1000E+00	0.5	2	THYROID
CYCLOHEXANE	0.5900E-04	0.5	2	KID&LIV
12-DCBENZENE	0.3400E-03	0.5	2	KID&LIV
14-DCBENZENE	0.4300E-03	0.5	2	LIVER
12-DCETHANE	0.6900E-01	1.0	1	CANCER
11-DCETHENE	0.1470E+00	1.0	1	CANCER
DICHLOROMETHANE	0.4500E-02	1.0	1	CANCER
12-DCPROPANE	0.3900E-01	1.0	1	CANCER
DCPROPANOLS	0.3900E-01	1.0	1	CANCER
13-DCPROPENE	0.9400E+01	0.5	2	KIDNEY
DIMETHOATE	0.5310E+01	0.1	2	BLD ENZ
DIMETHYL ALKYLAMINES	0.4050E-02	0.5	2	LIVER
13-DINITROBENZENE	0.8860E-01	0.1	2	BLOOD
24-DINITROTOLUENE	0.3100E+00	1.0	1	CANCER
DINOSEB	0.3200E-03	1.0	2	EMBRYO
ENDOSULFAN	0.3000E-02	0.5	2	KIDNEY
EPICHLOROHYDRIN	0.9900E-02	1.0	1	CANCER
ETHYLBENZENE	0.5760E-03	0.5	2	KID&LIV

TABLE D-2

TOXICITY PARAMETERS (CONT)

CONSTITUENT	UNIT RISK (H)	SCALING FACTOR (S)	SHAPE FACTOR (K)	TYPE OF EFFECT
ETHYLENE OXIDE	0.1300E+01	1.0	1	CANCER
FLUORIDES	0.1500E+08	0.5	4	TEETH
FORMALDEHYDE	0.7700E+00	0.5	2	WEIGHT
HEXACHLOROBENZENE	0.1670E+01	1.0	1	CANCER
HEXACHLOROBUTADIENE	0.7750E-01	1.0	1	CANCER
HEXACHLOROCYCLOPENT	0.1000E+07	0.1	2	BLOOD
HEXACHLOROETANE	0.1420E-01	1.0	1	CANCER
HYDROQUINONE	0.2500E+00	0.5	2	WEIGHT
LEAD	0.1250E+10	0.1	4	BLOOD
LINDANE	0.1330E+01	1.0	1	CANCER
M.E.KETONE	0.1100E-06	1.0	2	EMBRYO
M.I.KETONE	0.4480E-03	0.5	2	KIDNEY
MALEIC ANHYDRIDE	0.2780E-05	0.5	2	KIDNEY
MERCURY	0.6900E+00	0.5	2	KIDNEY
METHOMYL	0.6940E-02	0.5	2	BLD&SPL
METHYL CHLORIDE	0.9850E-03	0.5	2	KIDNEY
METHYL ISOCYANATE	0.7900E+01	0.5	2	LUNGS
METHYL METHACRYLATE	0.2500E-04	0.1	2	WEIGHT
MOLYBDENUM	0.1480E+03	0.5	2	KID&LIV
NAPHTHALENE	0.1000E-03	0.5	2	EYE
NAPHTHOQUINONE	0.2500E+00	0.5	2	WEIGHT
NICKEL	0.9000E+01	1.0	2	REPROD
NITROBENZENE	0.1800E-01	0.5	2	MULT ORG
4-NITROPHENOL	0.1800E-01	0.5	2	MULT ORG
PARALDEHYDE	0.1590E-03	0.5	2	TRACHEA
PARATHION	0.6940E+06	0.1	2	BLD ENZ
PCB-1254	0.4340E-01	1.0	1	CANCER
PCNITROBENZENE	0.7000E+00	1.0	1	CANCER
PCPHENOL	0.1600E-01	1.0	2	EMBRYO
PHENOL	0.1000E-01	0.5	2	KIDNEY
PHTHALIC ANHYDRIDE	0.4000E-06	0.5	2	WEIGHT
PYRIDINE	0.6600E-01	0.5	2	NEURO
2378-TCDD	0.1600E+06	1.0	1	CANCER
TDI	0.4300E-02	1.0	1	CANCER
1112-TCETHANE	0.8100E-02	0.5	2	NEURO
1122-TCETHANE	0.2000E+00	1.0	1	CANCER
TETRACHLOROETHYLENE	0.3500E-01	1.0	1	CANCER
THALLIUM	0.3090E+02	0.5	2	WEIGHT
TOLUENE	0.9400E-03	0.1	2	WEIGHT
TOLUENE-2,4-DIAMINE	0.2900E+00	1.0	1	CANCER
TOXAPHENE	0.1130E+01	1.0	1	CANCER
124-TCBENZENE	0.2000E-01	0.5	2	KID&LIV
111-TCETHANE	0.1600E-02	1.0	1	CANCER
112-TCETHANE	0.6800E+00	1.0	1	CANCER
TRICHLOROETHYLENE	0.1900E-01	1.0	1	CANCER
VANADIUM	0.3000E-01	0.5	2	NEURO
VINYL CHLORIDE	0.1750E-01	1.0	1	CANCER
XYLENE	0.2200E-02	0.5	2	LIVER
ZINC	0.1000E-03	0.5	2	ENDOCRINE

The secondary sources listed above were generally based on critical, expert scientific review and are usually reliable sources of information on inherent hazard. We did, however, build in some safeguards. After identifying the secondary sources that indicated hazardous effects at the lowest dose levels, for example, we obtained and briefly reviewed the primary reference in most cases. Where questions arose concerning the validity of the toxicological evidence for a particular compound as reported in the secondary sources, we also reviewed several primary references. We established our inherent-hazard data base on the basis of the best-supported evidence.

4. LIMITATIONS AND UNCERTAINTIES IN CHEMICAL RISK ASSESSMENT

4.1 General Risk Assessment Limitations

The procedures described in this appendix for establishing the risks of environmental agents are based on data that vary in quality and quantity among different chemicals. Clearly, some chemicals have been far more fully tested for toxicity than others; such differences are almost certainly due to statutory requirements which impose such testing on certain classes of chemicals before they can be accepted into commerce (e.g., pesticides, food and color additives, drugs). The Toxic Substances Control Act (15 USC 2601 et seq., 1976) is designed to provide for similar testing on other classes of chemicals in commerce, but this Act is of relatively recent origin and its affect is only recently being felt. An initiative by the Department of Health and Human Services -- the National Toxicology Program -- is also yielding data on a large number of commercial products, although most of the Program's data has been limited to carcinogenicity. Thus, while there are significant attempts to acquire toxicity data on all commercially important chemicals, it will likely be many years before a relatively complete and uniform data base will be available for these substances.

The fact that data bases vary in quality and quantity among different chemicals introduces uncertainty, and the type and degree of uncertainty varies from one substance to another. Thus, for example, one chemical may have been well-tested for subchronic toxicity, but its possible carcinogenic effects may not have been studied; whereas another substance may have been tested for carcinogenicity but may not have been tested for teratogenic effects.

The issue becomes more complex when test quality is considered: a substance to which many people are exposed at high levels and which may have appeared not to exhibit carcinogenic properties in a series of chronic animal tests that were probably not fully adequate in design to test the hypothesis of carcinogenic action, may be of more concern than a substance to which few people are exposed at low levels and which has been found to be weakly carcinogenic in a single well-designed study. Judging what should be done with data of these types is difficult, and there are no precise rules to guide risk assessors. As a result, many of the uncertainties in risk assessment are chemical-specific and cannot be reduced to general statements. However, an adequate risk assessment should contain a description of these types of uncertainties and how they were considered in arriving at conclusions about risk (NRC, 1983).

The risk assessments are also based on certain biologically plausible, yet untested, assumptions and inferences. Among the more important inferences are those concerning the similarities of humans and test animals and the nature of dose-response functions at dose levels well below the range of observable dose-response relations (NRC, 1983).

Many of the methods of risk assessment we have discussed are widely used by various committees of the National Research Council, and by the various regulatory agencies. Although these uses do not remove scientific uncertainty, they reveal that these methods reflect the best available scientific knowledge concerning the health effects and risks of environmental chemicals. There are no methods known to be superior to these methods for protection of health.

4.2 Risk Assessment Limitations Specific to Hazardous Waste Sites

The risk to human health posed by materials at a hazardous waste site is a function of two major factors:

1. The inherent hazard of the materials at the site, which determines the types of adverse effects (e.g., cancer, birth defects, kidney damage) they might be capable of causing, and the relationships between exposure and magnitude of effect; and

2. The magnitude of human exposure to the materials (the dose), which determines whether and to what extent the adverse effects are likely to occur.

Unfortunately, there is considerable uncertainty associated with both of these factors and it is not now possible to produce point estimates of human risk from any specific hazardous waste site without a fairly large band of error. There are additional sources of uncertainty, the more important of which are the following:

- Most waste sites contain complex mixtures of chemicals, many of which have not bee chemically characterized. No data are available on the toxic properties of any of the complex mixtures that comprise hazardous wastes;

- Although toxicity data on many of the individual chemical components of wastes are available, in many cases the data are highly limited and do not afford a picture of the full range of the adverse effects a chemical might display;

- Most of the toxicity data available on the individual components of wastes have been collected in experimental studies, involving laboratory animals. For the types of potential hazards of concern in this model -- delayed or chronic toxic effects -- there is very little information reflecting direct human experience;

- There is great variation in the type and severity of toxicity produced by the individual components of hazardous wastes. Thus, for example, some of the substances are carcinogenic, others cause birth defects or reproductive disorders, and others cause damage to particular organs or systems; and

- Although there is considerable experimental information on the relationships between exposure to hazardous waste components and the magnitude of resulting adverse effects (dose-response relationships), the data are limited to a relatively narrow range of exposures. The low end of the exposure range for which data are available is ordinarily higher than the range of human exposures that are likely to be encountered in environmental settings.

As Phase II of the model development is completed, the error bands associated with point estimates of human risk from specific waste sites will be greatly reduced to an acceptable level of confidence.

In this appendix we described a means for systematically incorporating toxicity data and exposure information into a methodology that provides a measure of human risk. The risk assessment methodology adopts, with some modifications, the traditional methods of toxicology and exposure analysis and should provide a degree of accuracy comparable to that provided by these traditional methods. Application of the methodology provides an approximation of the level of human health risk associated with land disposal facilities, with a precision that is matched to the level of precision required to use the risk values in analyzing trade-offs among costs and risks.

The model incorporates a variety of simplifying assumptions to deal with the major sources of uncertainty listed above. In every case, we attempted to reveal explicitly the nature of the assumption and its justification. Where possible we indicated the influence of the assumption upon the outcome of the analysis. Incorporation of assumptions in the absence of knowledge or data is a common feature of all risk assessments, and is necessary if health effects data are to be given any consideration in decision-making.

4.3 Risk Assessment Limitations Specific to the Model

In addition to the general limitations of risk assessment discussed above are uncertainties resulting from the assumptions within the specific Liner Location Risk and Cost Analysis Model methodology. We have listed some of the more significant sources of uncertainty below:

- The quadratic dose-response model for non-carcinogens, while based on an empirical study (Attachment 1), has not been widely used or validated by other investigators.
- The study that was the basis for assigning K=2 for non-carcinogens was limited to 15 chemicals and 63 sets of dose-response data.
- The assumptions made to derive H for non-carcinogens when the animal study data are not reported in sufficient detail (i.e., setting $R_0 = 0.1$ or 1.0).
- The arbitrary assignment of 0.1 or 0.5 as the value for the scaling factor to compensate for overestimation of graded effects.

These additional sources of uncertainty relate the assessment of risk for non-carcinogens. Estimation of explicit probabilistic risks for non-carcinogens is not widely practiced, and there is limited experience on which to base an approach. Thus, it is natural that there is more uncertainty in our methods for these chemicals.

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ATTACHMENT 1 TO APPENDIX D

ANALYSIS OF DOSE-RESPONSE CURVES FOR NON-CANCER EFFECTS 1/

This attachment explains the use of a non-linear relationship between human health risks and exposure to hazardous substances. There are theoretical reasons for assuming a linear relationship between dose and risk for carcinogenic effects at low doses, and linear methods have been widely applied to carcinogens. However, the assumption of linearity is less appropriate for effects that do not have a molecular-biologic origin 2/ or that rarely occur in unexposed populations. Effects such as these may have a non-linear or a threshold dose response. If linearity is assumed for an effect that actually follows a non-linear dose response, the estimated response probability is apt to be greatly overestimated at low doses.

The model assumes that the health effect response varies as d^k, where d represents dose or exposure and k is a constant that defines the shape of the curve (for linear dose response, $k = 1$). This approach is flexible and is capable of approximating reasonably well any dose-response relation. For example, there is little difference between the policy implications of a threshold response and a non-linear response with a large k, because at very low doses, the health risks will be small enough to be negligible.

In this attachment, we discuss possible values of k. Because most toxicological studies are not designed to estimate the dose response, values for k must be selected generically for broad classes of health

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1/ This report is also Appendix F to the RCRA Risk-Cost Analysis Model, Phase III Report.

2/ D. Hattis, "From Presence to Health Impact: Models for Relating Presence to Exposure to Damage" in Analyzing the Benefits of Health, Safety, and Environmental Regulations, M.I.T. Center for Policy Alternatives (1982).

effects, rather than being estimated for individual pollutants from toxicological data derived specifically from these pollutants. We compile dose-response data from the literature and study the values of k predicted by these data. Of particular interest is whether values of k greater than 1 are suggested by these data, and whether particular values of k appear to be associated with certain types of data or health effects. The discussion is limited to non-carcinogenic effects.

1. METHODOLOGY

1.1 Data Collection and Categorization

We conducted a search of roughly 100 toxicological papers for dose-response data on non-carcinogenic health effects. After screening, useable data were obtained from only 16 of these papers. We considered only experimental animal data. We categorized the data sets by type (either quantal or continuous), animal species, chemical, and type of effect. Three categories of effects were considered: teratogenic, other reproductive, and non-reproductive. We classified reproductive effects that resulted in permanent malformations as teratogenic. Teratogenic effects included cleft palate, palatal anomalies, malformed fetuses, skeletal anomalies, uni- and bilateral 16th rib, sternal defects, wavy ribs, rib anomalies, sternebrae anomalies, and vertebrae anomalies. Other reproductive effects included intestinal hemorrhage, unhealthy fetuses, and delayed bone ossification. Non-reproductive effects primarily involved organ weights or weights of whole animals.

1.2 Screening the Data

The experimental designs in the reviewed papers were highly variable with respect to numbers of animals, number of dose levels, and spacing of dose levels. The statistical significance of the experimental results also differed. Because each of these factors can have a considerable effect upon the estimate of k, and upon the precision of the estimate, we decided to establish certain minimal criteria for inclusion of a set of dose-response data in our analysis. These criteria, discussed below, were as follows:

(1) At least 4 dose levels (including control);

(2) At least 100 animals;

(3) At least 2 doses less than an order of magnitude apart;

(4) Difference between response in controls and highest dose group had to be statistically significant at the 5 percent level;

(5) A goodness-of-fit test had to yield a p-value greater than 0.01. If the p-values were less than 0.01, the data at the highest dose were deleted and the test was reapplied. This procedure was repeated until a p-value greater than 0.01 was obtained; the data providing this fit were used in the analysis. If this procedure did not produce a data set with a p-value greater than 0.01 that satisfied the first 4 criteria, we did not use the data set.

The absolute minimum number of doses required to estimate k is three. We therefore decided that a data set should have at least four doses to be included in this study. It would be desirable to have even more levels. However, we did not find enough data sets having five or more dose levels.

The fewer animals in a study, the less ability it has to discriminate among different values for k. The requirement of at least 100 animals was selected arbitrarily. Its use resulted in the deletion of a number of data sets that involved only five or six animals per dose, but otherwise satisfied the selection criteria.

Toxicological experiments often use doses spaced exactly an order of magnitude apart. Frequently in experiments with doses so widely spaced, an effect is measurable only at the highest dose, and responses at all lower doses are very similar to responses in controls. Such data, even if they involve large number of animals, generally do not furnish very precise estimates of k. We decided that, as a minimum, there should be at least two doses less than an order of magnitude apart.

We also decided that an effect should satisfy a minimal requirement for statistical significance. Data sets showing insignificant effects will not permit k to be estimated precisely.

Finally, we decided that data should satisfy a goodness-of-fit criterion. We included this criterion chiefly to eliminate data sets in which the response at high doses is incompatible with the dose-response trend, or value of k, suggested by lower dose data. There are a number of reasons why responses at the highest experimental dose might not be indicative of the shape of the curve at lower doses. For example, high doses might saturate the mechanisms leading to responses at lower doses, causing the dose-response curve to flatten out at the higher doses. The inclusion of a goodness-of-fit criterion should offer some protection against this occurrence. The specific goodness-of-fit tests utilized are described in Section 4 below. A p-value of .01 dictates that we reject data from the highest dosage only when we are at least 99 percent confident that the data do not fit. We initially tried a cut-off p-value of 0.05, but too few data sets satisfied this criterion.

We designed the first four criteria to eliminate data sets that would provide a very imprecise estimate of k. The fifth criterion protects against certain types of bias in the estimates of k.

1.3 Analysis of Data

Each set of dose-response data which satisfied the five criteria was used to estimate k and to calculate statistical confidence limits for k. Different estimation procedures were required for quantal and continuous data. Quantal data contain information on the number of animals in which an effect occurred. Dose levels, the number of animals in a dose group, and the number of those in which the effect occurred are generally reported in the literature. Data concerning the number of animals with cleft palate are examples of quantal data. Continuous data, on the other hand, add information on the degree of the effect. Data concerning the gain or loss of weight are examples of continuous data. Continuous data generally include the dose levels, the number of animals in each dose group, the average response in each dose group, and either the standard error or the standard deviation for the response for each dose group. 1/

With either type of data, we estimated k by fitting a dose-response model to the data. For quantal data, we used the Weibull model

$$P(d) = 1 - \exp(-a - bd^k), \tag{1}$$

with a and b non-negative and k greater than or equal to 1, where P(d) represents the probability that an animal responds when exposed to dose d. The model applied to continuous data was

$$m(d) = a + bd^k, \tag{2}$$

where m(d) represents the mean response at a dose d and k is greater than or equal to 1. Using these models, we estimated the parameter k from each set of dose-response data by the method of maximum likelihood. Upper and lower 80 percent and 95 percent statistical confidence limits for k were also calculated from each data set. Details of the methods used for these calculations are furnished in Section 4.

1/ It appeared that perhaps "standard error" and "standard deviation" were sometimes used interchangeably in the toxicity literature reviewed in this investigation. Nevertheless, we did not attempt to second-guess the authors, but took the nomenclature used in the literature at face value.

It has been argued that, theoretically, k cannot be less than 1 for any biological effect. 1/ Consequently, in the estimation procedure, k was constrained to be no less than 1. An upper bound of 10 was also assumed for k. We made this assumption to avoid computational difficulties associated with very large values for k. The principal interest of this study was in k-values in the range between 1 and 3.

Several types of statistical analyses were performed on the estimated k-values. If the dose-response model used is appropriate and if k is truly 1, then the probability that the estimated value of k is 1 is asymptotically equal to ½. 2/ This fact formed the basis of a test of the null hypothesis that k = 1 for each category. The p-value of the test was calculated as

$$B(x;n,\tfrac{1}{2}),$$

where B is the cumulative binomial distribution, n is the number of data sets, and x is the number of data sets for which k was estimated as 1.

We used non-parametric tests to test whether values for k were significantly different for different categories of data. Multiple comparisons were made using the Kruskal-Wallis test and two-sample comparisons were based upon the Wilcoxon tests. 3/ Large sample approximations were used in these tests and SAS was used for the calculations.

1/ P. F. Ricci, E. A. C. Crouch, and K. S. Crump, "Scorebook on Technological Risk Assessment" (in preparation).

2/ Cf. K. S. Crump, H. A. Guess, and K. L. Deal, "Confidence intervals and tests of hypotheses inferred from animal carcinogenicity data," Biometrics 33, No. 2 (1977), pp. 437-451.

3/ E. I. Lehman, Nonparametrics: Statistical Methods Based on Ranks (San Francisco: McGraw-Hill International, 1975).

2. RESULTS

Table DD-1 shows how we distributed these data sets by data type, species, and type of health effect. In all, 63 sets of dose-response data obtained from 16 papers satisfied the criteria for inclusion in the study. Of these, 38 were quantal data and 25 were continuous data. Fifty-two of the data sets involved rats; 10 involved mice; and 1 involved hamsters. Table DD-2 contains the estimates of k and 80 percent and 95 percent upper and lower confidence limits for k. A compilation of the dose-response data used in the study and a listing of the papers from which they were obtained is provided in Table DD-7 (the papers are identified by a reference number cited in Table DD-2).

Table DD-3 presents the median estimates for k and each of the upper and lower confidence limits for k. Tables DD-4 and DD-5 contain the numbers of k and corresponding lower limits exactly equal to 1. (Because k was assumed to be at least 1, neither the estimates nor the lower limits for k could be less than 1.) The medians ranged from 1.70 to 2.26 for six different categories of data, with only 1 category -- non-reproductive effects -- having a median exceeding 1.87. Interestingly, all of the data sets were reasonably compatible with $k = 1$; a majority of the 80 percent and 95 percent lower limits were equal to 1 (Table DD-5).

Table DD-4 shows the results of the test of the hypothesis that $k = 1$. This hypothesis could be clearly rejected for all data, both quantal and continuous, for each type of health effect.

Table DD-6 contains the results of the Wilcoxon test for equality of k between various categories of data. The results of these tests do not suggest that the different types of data, or different categories of effects, have values of k which are inherently different. Similarly, a multiple comparison test for rejecting the equality of k for the three types of health effects did not come close to reaching significance ($p = 0.84$).

Table DD-1

NUMBER OF DATA SETS OF VARIOUS TYPES

Type of Effect	Type of Data Quantal	 Continuous	 Total
Teratogenic	22	5	27
Other Reproductive	14	8	22
Non-Reproductive	2	12	14
Total	38	25	63

Type of Effect	Species Rat	 Mouse	 Hamster	 Total
Teratogenic	22	5	0	27
Other Reproductive	16	5	1	22
Non-Reproductive	14	0	0	14
Total	52	10	1	63

Table DD-2

MAXIMUM LIKELIHOOD ESTIMATES (MLE) AND CONFIDENCE LIMITS FOR K

						Values of K				
Data Set ID	Ref. No.	Effect a/	Animal Species b/	Chem. c/	No. of Doses	MLE	80% Lower Limit	80% Upper Limit	95% Lower Limit	95% Upper Limit
				QUANTAL DATA						
6	11	2	1	1	5	1.00	1.00	1.06	1.00	1.16
7	18	2	1	1	6	1.55	1.25	1.87	1.00	2.19
8	24	1	2	1	6	1.50	1.02	2.08	1.00	2.76
9	24	2	2	1	6	1.72	1.03	2.65	1.00	3.86
34	1	2	1	2	4	3.77	2.68	10.00	2.19	10.00
36	4	2	1	2	5	1.00	1.00	1.41	1.00	1.95
37	4	2	1	2	5	1.03	1.00	1.48	1.00	2.17
38	4	2	1	2	5	1.00	1.00	1.15	1.00	1.55
39	4	2	1	2	5	1.79	1.11	2.63	1.00	4.02
41	25	1	1	2	4	5.27	3.84	10.00	3.09	10.00
42	25	1	1	2	4	3.08	2.08	4.90	1.53	10.00
43	25	1	1	3	4	10.00	3.44	10.00	1.25	10.00
58	53	3	1	5	6	3.96	3.48	4.50	3.08	5.13
59	53	3	1	4	6	3.37	3.01	3.77	2.68	4.17
84	56	1	1	6	4	1.00	1.00	1.95	1.00	10.00
87	56	1	1	6	4	2.22	1.31	10.00	1.00	10.00
93	57	2	1	7	4	4.17	2.31	10.00	1.44	10.00
97	57	2	1	7	4	10.00	4.71	10.00	3.58	10.00
112	58	1	1	8	4	1.40	1.08	1.73	1.00	2.08
113	58	1	1	8	4	1.33	1.02	1.67	1.00	2.00
115	58	1	1	8	5	1.74	1.45	2.06	1.20	2.33
117	58	1	1	8	5	1.18	1.00	1.63	1.00	2.33
118	58	1	1	8	5	1.02	1.00	1.24	1.00	1.47
120	58	1	1	8	5	1.00	1.00	1.35	1.00	1.93
122	58	1	1	8	5	1.00	1.00	1.19	1.00	2.44
123	58	1	1	8	5	1.47	1.00	10.00	1.00	10.00
124	58	1	1	8	4	2.15	1.37	3.10	1.00	5.17
125	58	1	1	8	4	10.00	1.00	10.00	1.00	10.00
127	58	1	1	8	5	10.00	1.00	10.00	1.00	10.00
128	58	1	1	8	5	1.00	1.00	1.21	1.00	2.51
139	63	2	3	4	4	4.57	3.59	10.00	3.06	10.00
170	71	2	1	13	5	1.10	1.00	1.42	1.00	1.81
173	71	1	1	13	4	10.00	5.78	10.00	4.16	10.00
175	71	1	1	13	5	4.45	3.26	10.00	2.56	10.00
177	71	1	1	13	5	2.29	1.82	2.85	1.44	3.48
185	77	1	2	16	4	1.00	1.00	1.21	1.00	1.61
186	77	1	2	17	5	2.26	1.33	3.13	1.00	4.17
187	77	1	2	17	4	1.00	1.00	1.14	1.00	1.56

Table DD-2 (Continued)

MAXIMUM LIKELIHOOD ESTIMATES (MLE) AND CONFIDENCE LIMITS FOR K

Data Set ID	Ref. No.	Effect a/	Animal Species b/	Chem. c/	No. of Doses	Values of K				
						MLE	80% Lower Limit	80% Upper Limit	95% Lower Limit	95% Upper Limit
				CONTINUOUS DATA						
54	53	3	1	5	6	1.32	1.00	1.71	1.00	2.35
55	53	3	1	5	6	1.00	1.00	1.12	1.00	1.40
56	53	3	1	4	6	2.65	1.00	4.99	1.00	10.00
57	53	3	1	4	6	1.00	1.00	1.10	1.00	1.40
132	59	2	1	9	4	10.00	1.00	10.00	1.00	10.00
133	59	2	1	9	5	1.69	1.00	2.00	1.00	2.41
134	59	2	1	9	4	1.16	1.00	1.34	1.00	1.54
135	59	2	1	9	5	1.17	1.00	1.27	1.00	1.38
153	27	3	1	3	4	10.00	1.00	10.00	1.00	10.00
154	27	3	1	3	4	10.00	1.00	10.00	1.00	10.00
156	27	3	1	3	4	10.00	1.00	10.00	1.00	10.00
157	27	3	1	3	4	1.14	1.00	1.55	1.00	2.42
158	27	3	1	3	4	1.00	1.00	1.38	1.00	2.08
160	4	3	1	2	5	1.12	1.00	10.00	1.00	10.00
162	4	3	1	10	5	1.87	1.00	3.14	1.00	7.71
164	4	3	1	11	6	10.00	1.00	10.00	1.00	10.00
165	24	2	2	1	6	1.00	1.00	1.22	1.00	2.30
166	71	2	1	12	4	3.87	1.00	10.00	1.00	10.00
167	71	2	1	13	5	3.66	1.00	5.23	1.00	10.00
168	71	2	1	12	4	10.00	1.00	10.00	1.00	10.00
169	71	2	1	13	5	1.27	1.00	1.61	1.00	2.00
181	76	2	2	3	7	2.37	1.00	2.72	1.00	3.17
182	76	2	2	3	7	1.40	1.00	1.52	1.00	1.65
183	76	2	2	3	6	2.14	1.00	2.44	1.00	2.76
184	76	1	2	3	4	4.54	1.00	5.03	1.00	5.67

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a/ The effects are coded as follows: 1=teratogenic; 2=other reproductive; 3=non-reproductive.

b/ The animal species are coded as follows: 1=rat; 2=mouse; 3=hamster.

c/ The chemicals are coded as follows: 1=2,3,7,8-Tetrachlorodibenzo-p-dioxin; 2=2,4-Dichlorophenoxyacetive acid; 3=2,4,5-Trichlorophenoxyacetic acid; 4=sodium arsenate; 5=sodium arsenite; 6=cadmium; 7=chloroform; 8=hexachlorobenzene; 9=carbon monoxide; 10=propylene glycolether ester of 2,4-D; 11=isooctyl ester of 2,4-D; 12=purified pentachlorophenol; 13=pentachlorophenol; 16=phenytoin, 17=primidone.

Table DD-3

MEDIANS OF k AND 80 PERCENT AND 95 PERCENT UPPER AND LOWER LIMITS OF k

Sample	Median k	80% Lower Limit	80% Upper Limit	95% Lower Limit	95% Upper Limit	Sample Size
Overall	1.74	1	2.65	1	3.86	63
Quantal Data	1.73	1.06	2.64	1	3.94	38
Continuous Data	1.87	1	2.72	2.	3.17	25
Teratogenic Effects	1.70	1	2.08	1	2.76	27
Other Reproductive Effects	1.76	1	2.53	1	3.51	22
Non-Reproductive Effects	2.26	1	4.14	1	6.42	14

Table DD-4

RESULTS FROM TEST OF HYPOTHESES k EQUALS 1 VERSUS k GREATER THAN 1

	Number of k = 1	Number of k Greater Than 1	Total	p-value b/
Overall	13 (20.6) a/	50	63	0.000015
Quantal Data	9 (23.7)	29	38	0.00083
Continuous Data	4 (16.0)	21	25	0.00046
Teratogenic Effects	5 (18.5)	22	27	0.00076
Other Reproductive Effects	5 (22.7)	17	22	0.0085
Non-Reproductive Effects	3 (21.4)	11	14	0.029
Reproductive Effects	10 (21.3)	39	47	0.000049
Non-Teratogenic Effects	8 (22.2)	28	36	0.00060

---

a/ Figures in parenthesis are percentages.

b/ This p-value represents the probability that k=1.

Table DD-5

NUMBER OF 80% AND 95% LOWER LIMITS OF k THAT ARE EQUAL TO 1

Sample	80%	95%
Overall	41 (65.1) a/	50 (79.4) a/
Quantal Data	16 (41.2)	25 (65.8)
Continuous Data	25 (100)	25 (100)
Teratogenic Effects	15 (55.6)	20 (74.1)
Other Reproductive Effects	14 (63.6)	18 (81.8)
Non-Reproductive Effects	12 (85.7)	12 (85.7)
Reproductive Effects	29 (61.7)	38 (80.9)
Non-Teratogenic Effects	26 (72.2)	30 (83.3)

---

a/ Figures in parenthesis are percentages.

Table DD-6

WILCOXON TWO-SAMPLE TESTS OF EQUALITY OF k

Quantal Data vs. Continuous Data	.57
Reproductive Effects vs Non-Reproductive Effects	.65
Teratogenic Effects vs Non-Teratogenic Effects	.93

Table DD-7

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

QUANTAL DATA

#6 - Intestinal Hemorrhage

Dose (ug/kg/day)	0.0	0.03	0.125	0.5	2.0
Responses	0	0	18	36	4
Total Animals	246	115	127	99	7

#7 - Unhealthy Fetuses

Dose (ug/kg/day)	0.0	0.125	0.25	0.5	1.0	2.0
Responses	0	0	1	3	6	3
Total Animals	34	38	33	31	16	7

#8 - Cleft Palate

Dose (ug/kg/day)	0.0	0.001	0.01	0.1	1.0	3.0
Responses	0	2	0	1	4	10
Total Animals	34	41	19	17	19	14

#9 - Dialated Renal Pelvis

Dose (ug/kg/day)	0.0	0.001	0.01	0.1	1.0	3.0
Responses	0	0	0	0	1	4
Total Animals	34	41	19	17	19	14

#34 - F1b Generation Pups that did not Survive until Weaning

Dose (mg/kg/day)	0.0	6	30	90
Responses	55	53	51	114
Total Animals	185	213	178	142

#36 - Subcutaneous Edema

Dose (mg/kg/day)	0.0	12.5	25	50	75
Responses	0	0	3	3	3
Total Animals	180	78	95	69	75

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#37 - Delayed Ossification of Sternebrae

Dose (mg/kg/day)	0.0	12.5	25	50	75
Responses	18	10	16	19	23
Total Animals	205	85	103	77	82

#38 - Delayed Ossification of Skull Bones

Dose (mg/kg/day)	0.0	12.5	25	50	75
Responses	1	5	3	8	9
Total Animals	205	85	103	77	82

#39 - Lumbar Ribs

Dose (mg/kg/day)	0.0	12.5	25	50	75
Responses	0	0	1	2	4
Total Animals	205	85	103	77	82

#41 - Malformed D_1 Fetuses

Dose (mg/kg/day)	0.0	25	50	100
Responses	12	18	21	73
Total Animals	92	120	129	106

#42 - Malformed D_2 Fetuses

Dose (mg/kg/day)	0.0	25	50	100
Responses	6	24	24	88
Total Animals	104	143	153	165

#58 - Enlarged Bile Ducts

Dose (ppm)	0.0	18.63	31.25	62.5	125	250
Responses	0	1	0	1	7	45
Total Animals	50	50	50	48	50	50

#59 - Enlarged Bile Ducts

Dose (ppm)	0.0	31.25	62.5	125	250	400
Responses	1	0	0	0	25	42
Total Animals	50	50	50	50	50	48

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#84 - Malformed Fetuses

Dose (mg/kg/day)	0.0	10	30	100
Responses	0	1	1	5
Total Animals	221	245	219	209

#87 - Malformed Fetuses

Dose (mg/kg/day)	0.0	3	10	30
Responses	1	1	2	10
Total Animals	182	203	205	178

#93 - Infertile Females

Dose (ppm)	0.0	30	100	300
Responses	9	9	5	17
Total Animals	77	31	20	20

#97 - Resorptions

Dose (ppm)	0.0	30	100	300
Responses	63	24	16	20
Total Animals	769	291	278	33

#112 - Skeletal Anomalies

Dose (mg/kg/day)	0.0	40	60	80
Responses	11	43	55	51
Total Animals	125	127	123	84

#113 - Uni- and Bilateral 16th Rib

Dose (mg/kg/day)	0.0	40	60	80
Responses	6	38	45	47
Total Animals	125	127	123	84

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#115 - Sternal Defects

Dose (mg/kg/day)	0.0	40	60	80	120
Responses	3	10	18	18	43
Total Animals	125	127	123	84	119

#117 - Skeletal Anomalies

Dose (mg/kg/day)	0.0	10	20	40	60
Responses	5	5	12	19	25
Total Animals	80	79	91	87	96

#118 - Uni- and Bilateral 16th Rib

Dose (mg/kg/day)	0.0	10	20	40	60
Responses	0	4	8	15	25
Total Animals	80	79	91	87	96

#120 - Sternal Defects

Dose (mg/kg/day)	0.0	10	20	40
Responses	0	1	5	5
Total Animals	80	79	91	87

#122 - Skeletal Anomalies

Dose (mg/kg/day)	0.0	10	20	40	80
Responses	2	8	7	13	8
Total Animals	80	67	89	86	67

#123 - Uni- and Bilateral 16th Rib

Dose (mg/kg/day)	0.0	10	20	40	80
Responses	2	6	1	6	6
Total Animals	80	67	89	86	67

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#124 - Wavy Ribs

Dose (mg/kg/day)	0.0	10	20	40
Responses	0	0	2	6
Total Animals	80	67	89	86

#125 - Sternal Defects

Dose (mg/kg/day)	0.0	10	20	40
Responses	0	2	1	5
Total Animals	80	67	89	86

#127 - Skeletal Anomalies

Dose (mg/kg/day)	0.0	10	20	40	80
Responses	11	11	16	8	13
Total Animals	92	106	93	90	85

#128 - Uni- and Bilateral 16th Rib

Dose (mg/kg/day)	0.0	10	20	40	80
Responses	2	7	9	8	13
Total Animals	92	106	93	90	85

#139 - Resorbed or Dead Embryos

Dose (mg/kg/day)	0.0	5	20	40
Responses	6	6	89	39
Total Animals	136	36	255	39

#170 - Subcutaneous Edema a/

Dose (mg/kg/day)	0.0	5.8	15	34.7	50
Responses	6	2	8	16	8
Total Animals	33	18	16	19	13

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#173 - Rib Anomalies a/

Dose (mg/kg/day)	0.0	5.8	15	34.7	
Responses	0	0	0	18	
Total Animals	31	18	16	19	

#175 - Vertebrae Anomalies a/

Dose (mg/kg/day)	0.0	5.8	15	34.7	50
Responses	6	0	3	18	12
Total Animals	31	18	16	19	12

#177 - Sternebrae Anomalies a/

Dose (mg/kg/day)	0.0	5.8	15	34.7	50
Responses	5	2	2	17	10
Total Animals	31	18	16	19	12

#185 - Palatal Defects

Dose (mg/kg/day)	0.0	40	120	250	
Responses	0	0	7	19	
Total Animals	181	34	63	186	

#186 - Palatal Defects

Dose (mg/kg/day)	0.0	500	1250	2000	2500
Responses	0	3	8	1	5
Total Animals	210	188	214	19	33

#187 - Palatal Defects

Dose (mg/kg/day)	0.0	100	150	200	
Responses	1	16	11	15	
Total Animals	90	150	125	140	

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

CONTINUOUS DATA

#54 - Weight loss in males

Dose (ppm)	NUMBER	MEAN ± SD
.0	20	536.40 ± 32.4
15.63	23	531.90 ± 73.4
31.25	20	556.10 ± 67.9
62.50	20	520.60 ± 49.4
125.0	16	486.30 ± 67.9
250.0	15	435.60 ± 69.3

#55 - Weight loss in females

Dose (ppm)	NUMBER	MEAN ± SD
.0	15	351.80 ± 50.9
15.63	16	357.30 ± 61.5
31.25	17	336.40 ± 68.5
62.50	21	323.10 ± 52.1
125.0	24	289.70 ± 29.7
250.0	11	249.80 ± 29.7

#56 - Weight loss in males

Dose (ppm)	NUMBER	MEAN ± SD
.0	20	580.40 ± 81.5
31.25	18	562.10 ± 109.
62.50	21	574.10 ± 74.0
125.0	18	520.40 ± 156.
250.0	15	541.50 ± 90.1
400.0	11	443.90 ± 65.8

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#55 - Weight loss in females

Dose (ppm)	NUMBER	MEAN ± SD
.0	21	382.50 ± 61.7
31.25	19	352.40 ± 53.4
62.50	22	365.00 ± 65.9
125.0	18	321.80 ± 66.5
250.0	15	285.90 ± 75.3
400.0	17	269.60 ± 37.0

#132 - Percent of hematocrit

Dose (ppm)	NUMBER	MEAN ± SD
.0	53	33.28 ± 2.07
60.00	13	34.54 ± 1.66
125.0	10	34.40 ± 1.51
250.0	19	28.37 ± 3.13

#133 - Amount of hemoglobin

Dose (ppm)	NUMBER	MEAN ± SD
.0	53	9.09 ± .620
60.00	13	9.26 ± .420
125.0	10	9.13 ± .520
250.0	19	7.95 ± .950
500.0	23	6.51 ± .560

#134 - Heart weights

Dose (ppm)	NUMBER	MEAN ± SD
.0	36	0.50 ± .05
60.00	12	0.55 ± .06
125.0	10	0.59 ± .04
250.0	10	0.71 ± .04

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#135 - Fetal body weights

Dose (ppm)	NUMBER	MEAN ± SD
.0	54	3.08 ± .190
60.00	13	3.03 ± .310
125.0	10	2.85 ± .130
250.0	22	2.58 ± .260
500.0	25	1.95 ± .130

#153 - Body weight on day 314

Dose (ppm)	NUMBER	MEAN ± SD
.0	86	361.00 ± 28.0
3.000	50	363.00 ± 26.0
10.00	50	365.00 ± 28.0
30.00	50	347.00 ± 27.0

#154 - Total 48 hour urine volume

Dose (ppm)	NUMBER	MEAN ± SD
.0	96	38.00 ± 8.00
3.000	60	40.00 ± 10.0
10.00	60	36.00 ± 14.0
30.00	60	49.00 ± 11.0

#156 - Copro porphyrin - females

Dose (ppm)	NUMBER	MEAN ± SD
.0	96	9.60 ± 1.90
3.000	60	10.30 ± 3.50
10.00	60	9.20 ± .800
30.00	60	16.40 ± 7.00

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#157 - Uro porphyrin - males

Dose (ppm)	NUMBER	MEAN ± SD
.0	96	4.10 ± 1.80
3.000	60	4.50 ± 2.00
10.00	60	5.00 ± 3.07
30.00	60	7.70 ± 4.70

#158 - Kidney weights a/

Dose (ppm)	NUMBER	MEAN ± SD
.0	10	0.70 ± .09
3.000	10	0.72 ± .05
10.00	10	0.73 ± .05
30.00	10	0.79 ± .06

#160 - Body weight

Dose (ppm)	NUMBER	MEAN ± SD
.0	34	40.00 ± 5.83
12.50	16	38.00 ± 4.00
25.00	19	42.00 ± 8.72
50.00	20	35.00 ± 5.94
75.00	16	41.00 ± 8.00

#162 - Body weight

Dose (ppm)	NUMBER	MEAN ± SD
.0	34	7.10 ± 1.75
12.50	18	8.30 ± 2.12
25.00	18	6.80 ± 2.55
50.00	19	6.60 ± 1.31
75.00	18	5.90 ± 1.27

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#164 - Body weight

Dose (ppm)	NUMBER	MEAN ± SD
.0	34	7.10 ± 1.75
12.50	18	7.20 ± 1.70
25.00	18	6.90 ± 2.12
50.00	18	7.00 ± 1.27
75.00	17	6.80 ± 1.65
87.50	17	5.70 ± 1.24

#165 - Relative liver weight

Dose (ppm)	NUMBER	MEAN ± SD
.0	34	56.30 ± 5.60
.1000D-02	41	55.80 ± 5.80
.1000D-01	19	55.30 ± 6.20
.1000	17	58.30 ± 5.10
1.000	19	60.00 ± 8.00
3.000	14	63.40 ± 8.40

#166 - Maternal body weight on day 21

Dose (ppm)	NUMBER	MEAN ± SD
.0	33	397.00 ± 40.2
5.000	15	417.00 ± 23.2
15.00	18	402.00 ± 33.9
30.00	20	324.00 ± 17.9

#167 - Maternal body weight on day 21

Dose (ppm)	NUMBER	MEAN ± SD
.0	33	397.00 ± 40.2
5.000	18	412.00 ± 25.5
15.00	17	394.00 ± 33.0
30.00	19	393.00 ± 21.8
50.00	15	334.00 ± 34.9

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#168 - Weight gain on days 6-21

Dose (ppm)	NUMBER	MEAN ± SD
.0	33	139.00 ± 34.5
5.000	15	138.00 ± 31.0
15.00	18	142.00 ± 29.7
30.00	20	36.00 ± 13.4

#169 - Weight gain on days 16-21

Dose (ppm)	NUMBER	MEAN ± SD
.0	33	139.00 ± 34.5
5.000	18	132.00 ± 17.0
15.00	17	127.00 ± 20.6
30.00	19	103.00 ± 21.8
50.00	15	76.00 ± 34.9

#181 - Litter size

Dose (ppm)	NUMBER	MEAN ± SD
.0	31	10.10 ± 2.10
30.00	23	9.80 ± 2.28
45.00	8	9.40 ± .570
60.00	31	9.00 ± 2.02
75.00	5	7.40 ± .660
90.00	7	7.10 ± 1.77
120.0	3	2.70 ± 1.30

Table DD-7 (Continued)

COMPILATION OF DOSE-RESPONSE DATA USED IN THE STUDY

#182 - Fetal weight

Dose (ppm)	NUMBER	MEAN ± SD
.0	31	0.94 ± .04
30.00	23	0.89 ± .04
45.00	8	0.82 ± .04
60.00	31	0.75 ± .05
75.00	5	0.66 ± .03
90.00	7	0.62 ± .05
120.0	3	0.51 ± .04

#183 - Percent resorbed/litter

Dose (ppm)	NUMBER	MEAN ± SD
.0	31	6.50 ± 3.33
30.00	23	7.70 ± 4.09
45.00	8	12.90 ± 4.07
60.00	31	15.20 ± 6.34
75.00	5	28.40 ± 8.88
90.00	7	26.90 ± 8.15

#184 - Percent cleft palate/litter

Dose (ppm)	NUMBER	MEAN ± SD
.0	31	0.30 ± .480
30.00	23	1.10 ± 1.68
45.00	8	12.80 ± 6.90
60.00	31	23.00 ± 14.0

a/ Data set should not have been included.

3. CONCLUSIONS

We consider the work described in this appendix to be the nature of a pilot study rather than to be definitive. A much larger data base involving more chemicals and more data on each type of health effect would be needed in order to draw firm conclusions. If such a larger data base were obtained, it would be appropriate to categorize the data more finely with respect to type of health effect and chemical class. It would also be worthwhile to collect and analyze dose-response data on humans.

Overall, the results of this study strongly suggest that it is appropriate to use values of k larger than 1 for the effects studied (cf. Table DD-3). Although most of the individual data sets were compatible with k = 1, this apparently was because of small sample sizes. No significant differences were found between values of k when comparisons were made between quantal and continuous data, teratogenic and non-teratogenic data, or reproductive and non-reproductive data. The median values of k computed under various classifications were similar, ranging from 1.70 for teratogenic effects to 2.26 for non-reproductive effects. Although non-reproductive effects had a larger median k than reproductive effects, a much larger data base would be required to confirm this trend. The median k for the combined data sets was 1.74.

Carcinogenic data were not included in this study, and it would be interesting to see how k values determined from carcinogenicity data compare with those obtained in this study. However, even if k values from carcinogenicity data were greater than 1, the assumption of k = 1 might still be retained for carcinogenicity because there are theoretical grounds for believing that carcinogenic dose-responses are apt to be linear at low doses even if non-linearities are observed at higher doses.

Because no similar *a priori* basis exists for considering non-carcinogenic dose-responses to be linear, we used the median k values determined empirically in this study in the model

4. DETAILS OF ANALYTIC METHODS USED

This section is included as an addendum to explain in greater detail the analytic methods used in the study.

Quantal dose-response data is of the form (d_i, X_i, N_i), i = 1,...g, where g is the number of dose groups and d_i, X_i, and N_i are the dose, number of affected animals, and total number of animals, respectively. The likelihood of the data (L) is given by:

$$L = \pi_{i=1}^{g} \; {}^{N_i}_{X_i} \; P(d_i)^{X_i} \; [1 - P(d_i)]^{N_i - X_i} , \qquad (3)$$

where $P(d) = 1 = \exp(-a - bd^k)$.

This approach assumes different animals respond independently. Consequently, it may be somewhat in error when applied to litter-mates in a teratogenic study.

The goodness-of-fit test for quantal data is based upon the statistic

$$\sum_{i=1}^{g} \frac{[N_i P(d_i) - X_i]^2}{N_i P[d_i(1 - P(d_i))]}, \qquad (4)$$

where $P(d_i)$ is calculated from maximum likelihood estimates of a, b and k. This statistic approximates a chi-square distribution with g-3 degrees of freedom under the null hypothesis.

Continuous dose response data are of the form (d_i, X_i, s_i, N_i), i = 1,..., g, where g, d_i and N_i have the same meanings as above; and X_i, s_i are the sample mean and standard deviation of the responses in the ith dose group, respectively. Specifically

$$X_i = \left(\sum_{j=1}^{N_i} X_{ij}\right)/N_i, \qquad (5)$$

and

$$s_i^2 = \frac{1}{N_i - 1} \sum_{j=1}^{N_i} (X_{ij} - \bar{X}_i)^2 \qquad (6)$$

where X_{ij} is the measured response for the jth individual in the ith dose group. Sometimes standard errors are given rather than sample standard deviations(s), but these are related by the formula

$$[\text{standard error for ith dose group}] = s_i/N_i^{1/2}. \qquad (7)$$

It is assumed that the individual response X_{ij} has a normal distribution with mean

$$m(d_i) = a + bd_i^k \qquad (8)$$

and variance σ_i^2. Assuming different animals respond independently, the likelihood of the data (L) is given by

$$L = \prod_{i=1}^{g} (2\pi)^{-N_i/2} \sigma_i^{-N_i} \exp \frac{-(N_i-1)s_i^2 - N_i[\bar{X}_i - m(d_i)]^2}{2\sigma_i^2} \qquad (9)$$

The goodness-of-fit test for continuous data was based upon the F statistic for testing the lack of fit: 1/

$$\frac{SSE - SSE(pure)}{s^2(g-3)}, \qquad (10)$$

where:

$$SSE = \sum_{i=1}^{g} \sum_{j=1}^{N_i} [X_{ij} - m(d_i)]^2, \qquad (11)$$

$$SEE(pure) = \sum_{i=1}^{g} \sum_{j=1}^{N_i} (X_{ij} - X_i)^2, \qquad (12)$$

$$s^2 = \frac{SSE(pure)}{\sum_{i=1}^{g} N_i - g}, \qquad (13)$$

and the $m(d_i)$ is calculated from the maximum likelihood estimates of a, b, and k. This statistic can be shown, under certain conditions, to have an F-distribution with g-3 and $(\sum_{i=1}^{g} N_i - g)$ degrees of freedom in the numerator and denominator, respectively, under the null hypothesis.

With either quantal or continuous data, confidence limits are calculated using the likelihood method. 2/ Upper limits for k are calculated as solutions to the optimization problem:

Maximize k
subject to the constraint
$2[\mathrm{Log}(L_{max}) - \mathrm{Log}(L)] = c$ (14)

Lower limits are calculated similarly. (Minimize k subject to the constraint $2[\mathrm{Log}(L_{max}) - \mathrm{Log}(L)] = c$.) For 80 percent (one-sided) limits c = 0.70832 and for 95 percent limits c = 2.70553.

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APPENDIX E

COST MODEL

Appendix E to the liner location report shows how Pope-Reid Associates (PRA) and Sobotka & Co., Inc. (SCI) calculated costs for landfills and surface impoundments of different designs and sizes, and the results of these calculations. To calculate costs we:

- specified designs and sizes
- estimated the engineering costs for these designs and sizes
- converted the engineering costs to economic measures

Our results show that there are substantial returns to scale in land disposal so that the per unit disposal cost decreases as the facility size increases, and that the cost of land disposal increases as the design of the facility becomes more stringent. Although the two contracting teams worked closely together, PRA is primarily responsible for the engineering analysis, while SCI is responsible for the economic analysis.

1. ENGINEERING COSTS

We used the Pope-Reid Associates (PRA) Facilities Design Computer Cost Model to estimate construction and closure costs for six different liner configurations for landfills and surface impoundments.

This model uses data from standard building, construction, and site work cost manuals 1/, vendor information, and professional judgement to estimate the costs of significant design and engineering components of specified

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1/ Means Site Work Cost Data. Third Annual Edition, 1984. R.S. Means Company, Inc., Kingston, Massachusetts.

designs. The resulting costs are often referred to as "engineering costs." The model estimates initial capital costs (land, constructing the first year's cell for landfills or excavating and installing liners for surface impoundments, building the infrastructure, etc.), annual capital costs (building the next year's cell and closing the last year's cell for landfills), closure costs (covering the final cell for landfills or covering the surface impoundment, decontaminating equipment, monitoring, and certifying closure), and operating and maintenance (O&M) costs associated with the technical aspects of operating the facility. For surface impoundments, it also estimates the frequency and cost of dredging.

The cost model stimulates the significant design, engineering, and cost components of facility construction. A person using the model has a great degree of flexibility in selecting facility specifications, liner designs, cover characteristics, and material costs. Consequently, it is easy to add other liner configurations or modify those we used in this analysis to evaluate a wide range of regulatory options.

The landfill and surface impoundment designs appear in Tables E-1 and E-2, respectively. For landfills and surface impoundments, both the unlined and the clay lined designs (designs 6 and 3) comply only with Part 265; the single synthetic (design 1) complies with Part 264; while the double synthetic, synthetic/clay, and double synthetic/clay designs (2, 4, and 5 respectively) not only comply with Part 264 but also include features that Part 264 does not presently require.

For each design, we estimated engineering costs for several facility sizes. Although the cost model is flexible with respect to facility size and permits us to determine costs for facilities of any sizes, for this application we selected sizes OSW had previously used in its analyses of land disposal regulations. The landfill sizes are:

- 500 MT/year
- 2,000 MT/year
- 5,000 MT/year

TABLE E-1. LANDFILL DESIGNS

Design Component	1 (Single Syn)	2 (Double Syn)	3 (Single Clay)	4 (Syn/Clay)	5 (Double Syn/Clay)	6 (Baseline-Unlined)
FINAL COVER	Revegetation 0.6 m select fill layer Geotextile filter layer 0.3 m sand layer 30-mil syn Geotextile support layer 0.6 m clay layer	Same as Design 1	Same as Design 1	Same as Design 1	Same as Design 1	Revegetation 0.15 m select fill layer
CONTAINMENT SYSTEM	0.15 m earth fill layer Geotextile filter layer 0.3 m sand layer 36-mil syn Geotextile support layer	0.15 m earth fill layer Geotextile filter layer 0.3 m sand layer 36-mil syn 0.3 m sand layer 36-mil syn Geotextile support layer	0.15 m earth fill layer Geotextile filter layer 0.3 m sand layer 0.6 m clay layer	0.15 m earth fill layer Geotextile filter layer 0.3 m sand layer 36-mil syn Geotextile support layer 0.6 m clay layer	0.15 m earth fill layer Geotextile filter layer 0.3 m sand layer 36-mil syn 0.3 m sand layer 36-mil syn Geotextile support layer 0.6m clay layer	None

TABLE E-2. SURFACE IMPOUNDMENT DESIGNS

Design Component	1 (Single Syn)	2 (Double Syn)	3 (Single Clay)	4 (Syn/Clay)	5 (Double Syn/Clay)	6 (Baseline-Unlined
FINAL COVER	Revegetation	Same as Design 1	Same as Design 1	Same as Design 1	Same as Design 1	Revegetation
	0.6 m select fill layer					0.15 m select fill layer
	Geotextile filter layer					
	0.3 m sand layer					
	30 mil syn					
	Geotextile support layer					
	0.6 m clay layer					
CONTAINMENT SYSTEM	36-mil syn	36-mil syn	0.6 m clay layer	36-mil syn	36-mil syn	None
		0.3 m sand layer		0.3 m sand layer	0.3 m sand layer	
		36-mil syn		0.6 m clay layer	36-mil syn	
		Geotextile support layer			Geotextile support layer	
					0.6 m clay layer	

- 7,000 MT/year
- 15,000 MT/year
- 35,000 MT/year
- 60,000 MT/year
- 123,000 MT/year

The surface impoundment sizes are:

- 0.25 acre
- 0.50 acre
- 1.00 acre
- 2.00 acre
- 5.00 acre
- 11.00 acre

1.1 Landfill Costs

The capital costs 1/ for landfills appear in Tables E-3 through E-14. For each facility design, there are capital costs for year 1 (Tables E-3-E-8) and annual capital costs for years 2 through 20 (Tables E-9-E-14). The year 1 capital costs consist of the capital investment for the entire landfill (land, heavy equipment, fence, warning signs, etc.). This expense is the largest part of the capital expense for all designs and sizes. There is also an initial capital expense for constructing the first cell; the cost of building the first cell is never more than about 33 percent of the first year's direct capital and for very small landfills can be less than 10 percent of direct capital costs.

The annual capital costs incurred in years 2 through 20 are for placing a final cover on the previous year's cell and constructing a new cell. Although baseline facilities have no liners, it is necessary to excavate, so there is a capital cost for excavation even for unlined facilities.

1/ These and all subsequent engineering costs are reported in 1st quarter 1984 dollars.

TABLE E-3

LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - UNLINED

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Office equipment					10.3	11.9	13.5	15.1
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	2.1	8.7	21.7	30.4	65.0	151.6	259.9	532.8
Total Direct Capital	227.5	306.4	444.5	496.9	827.2	1262.8	1867.2	2855.4

INDIRECT CAPITAL COSTS ($1000)								
Engineering - 5%	11.4	15.3	22.2	24.8	41.4	63.1	93.4	142.8
Inspection and testing - 3%	6.8	9.2	13.3	14.9	24.8	37.9	56.0	85.7
Construction and field expenses - 5%	11.4	15.3	22.2	24.8	41.4	63.1	93.4	142.8
Contractors fee - 10%	22.8	30.6	44.5	49.7	82.7	126.3	186.7	285.5
Start-up cost - 1%	2.3	3.1	4.4	5.0	8.3	12.6	18.7	28.6
Spare parts inventory - 1%	2.3	3.1	4.4	5.0	8.3	12.6	18.7	28.6
Interest during construction - 10%	22.8	30.6	44.5	49.7	82.7	126.3	186.7	285.5
Subtotal Indirect Capital	79.6	107.2	155.6	173.9	289.5	442.0	653.5	999.4
Working capital - 10%	30.7	41.4	60.0	67.1	111.7	170.5	252.1	385.5
Contingency - 10%	30.7	41.4	60.0	67.1	111.7	170.5	252.1	385.5
Total Indirect Capital	141.1	190.0	275.6	308.1	512.9	782.9	1157.7	1770.3
TOTAL FACILITY COST	368.6	496.4	720.1	805.0	1340.1	2045.7	3024.9	4625.7

TABLE E-4

LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE SYNTHETIC

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Fence & gates					80.1	98.5	111.0	136.4
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Signs	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Surface water control	8.6	12.8	16.3	18.2	22.7	30.6	36.1	47.0
Leachate treatment system	63.0	63.0	63.0	63.0	63.0	63.0	85.0	110.0
Groundwater wells	10.0	10.0	12.0	12.0	14.0	16.0	18.0	22.0
Office equipment					10.3	11.9	13.5	15.1
Laboratory equipment					25.0	25.0	25.0	25.0
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	24.5	44.4	73.7	92.6	157.7	312.8	482.0	906.0
Total Direct Capital	332.3	428.7	588.6	653.1	1125.5	1657.9	2365.2	3569.8

INDIRECT CAPITAL COSTS ($1000)								
Engineering - 10%	33.2	42.9	58.9	65.3	112.6	165.8	236.5	357.0
Inspection and testing - 5%	16.6	21.4	29.4	32.7	56.3	82.9	118.3	178.5
Construction and field expenses - 5%	16.6	21.4	29.4	32.7	56.3	82.9	118.3	178.5
Contractors fee - 10%	33.2	42.9	58.9	65.3	112.6	165.8	236.5	357.0
Start-up cost - 1%	3.3	4.3	5.9	6.5	11.3	16.6	23.7	35.7
Spare parts inventory - 1%	3.3	4.3	5.9	6.5	11.3	16.6	23.7	35.7
Interest during construction - 10%	33.2	42.9	58.9	65.3	112.6	165.8	236.5	357.0
Subtotal Indirect Capital	139.6	180.1	247.2	274.3	472.7	696.3	953.4	1499.3
Working capital - 10%	47.2	60.9	83.6	92.7	159.8	235.4	335.9	506.9
Contingency - 15%	70.8	91.3	125.4	139.1	239.7	353.1	503.8	760.4
Total Indirect Capital	257.5	332.2	456.2	506.2	872.3	1284.9	1833.0	2766.6
TOTAL FACILITY COST	589.8	760.9	1044.8	1159.3	1997.8	2942.8	4198.2	6336.4

TABLE E-5

LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - DOUBLE SYNTHETIC

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Fence & gates					80.1	98.5	111.0	136.4
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Signs	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Surface water control	8.6	12.8	16.3	18.2	22.7	30.6	36.1	47.0
Leachate treatment system	63.0	63.0	63.0	63.0	63.0	63.0	85.0	110.0
Groundwater wells	10.0	10.0	12.0	12.0	14.0	16.0	18.0	22.0
Office equipment					10.3	11.9	13.5	15.1
Laboratory equipment					25.0	25.0	25.0	25.0
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	31.7	61.6	102.7	129.0	215.9	419.7	632.0	1162.5
Total Direct Capital	339.5	445.9	617.6	689.5	1183.7	1764.8	2515.2	3826.3

INDIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Engineering - 10%	34.0	44.6	61.8	69.0	118.4	176.5	251.5	382.6
Inspection and testing - 5%	17.0	22.3	30.9	34.5	59.2	88.2	125.8	191.3
Construction and field expenses - 5%	17.0	22.3	30.9	34.5	59.2	88.2	125.8	191.3
Contractors fee - 10%	34.0	44.6	61.8	69.0	118.4	176.5	251.5	382.6
Start-up cost - 1%	3.4	4.5	6.2	6.9	11.8	17.6	25.2	38.3
Spare parts inventory - 1%	3.4	4.5	6.2	6.9	11.8	17.6	25.2	38.3
Interest during construction - 10%	34.0	44.6	61.8	69.0	118.4	176.5	251.5	382.6
Subtotal Indirect Capital	142.6	187.3	259.4	289.6	497.2	741.2	1056.4	1607.0
Working capital - 10%	48.2	63.3	87.7	97.9	168.1	250.6	357.2	543.3
Contingency - 15%	72.3	95.0	131.5	146.9	252.1	375.9	535.7	815.0
Total Indirect Capital	263.1	345.6	478.6	534.4	917.4	1367.7	1949.3	2965.4
TOTAL FACILITY COST	602.6	791.5	1096.2	1223.9	2101.1	3132.5	4464.5	6791.7

TABLE E-6

LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE CLAY

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Fence & gates					80.1	98.5	111.0	136.4
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Signs	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Surface water control	8.6	12.8	16.3	18.2	22.7	30.6	36.1	47.0
Leachate treatment system	63.0	63.0	63.0	63.0	63.0	63.0	85.0	110.0
Groundwater wells	10.0	10.0	12.0	12.0	14.0	16.0	18.0	22.0
Office equipment					10.3	11.9	13.5	15.1
Laboratory equipment					25.0	25.0	25.0	25.0
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	25.4	45.6	76.1	95.3	162.4	320.0	492.6	922.5
Total Direct Capital	333.2	429.9	591.0	655.8	1130.2	1665.1	2375.8	3586.3

INDIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Engineering - 10%	33.3	43.0	59.1	65.6	113.0	166.5	237.6	358.6
Inspection and testing - 5%	16.7	21.5	29.6	32.8	56.5	83.3	118.8	179.3
Construction and field expenses - 5%	16.7	21.5	29.6	32.8	56.5	83.3	118.8	179.3
Contractors fee - 10%	33.3	43.0	59.1	65.6	113.0	166.5	237.6	358.6
Start-up cost - 1%	3.3	4.3	5.9	6.6	11.3	16.7	23.8	35.9
Spare parts inventory - 1%	3.3	4.3	5.9	6.6	11.3	16.7	23.8	35.9
Interest during construction - 10%	33.3	43.0	59.1	65.6	113.0	166.5	237.6	358.6
Subtotal Indirect Capital	139.9	180.6	248.2	275.4	474.7	699.3	997.8	1506.2
Working capital - 10%	47.3	61.0	83.9	93.1	160.5	236.4	337.4	509.3
Contingency - 15%	71.0	91.6	125.9	139.7	240.7	354.7	506.0	763.9
Total Indirect Capital	258.2	333.2	458.0	508.2	875.9	1290.5	1841.2	2779.4
TOTAL FACILITY COST	591.4	763.1	1049.0	1164.0	2006.1	2955.6	4217.0	6365.7

TABLE E-7
LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE SYNTHETIC/CLAY

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Fence & gates					80.1	98.5	111.0	136.4
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Signs	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Surface water control	8.6	12.8	16.3	18.2	22.7	30.6	36.1	47.0
Leachate treatment system	63.0	63.0	63.0	63.0	63.0	63.0	85.0	110.0
Groundwater wells	10.0	10.0	12.0	12.0	14.0	16.0	18.0	22.0
Office equipment					10.3	11.9	13.5	15.1
Laboratory equipment					25.0	25.0	25.0	25.0
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	29.9	56.7	95.1	119.3	200.7	391.1	592.3	1093.6
Total Direct Capital	337.7	441.0	610.0	679.8	1168.5	1736.2	2475.5	3757.4

INDIRECT CAPITAL COSTS ($1000)								
Engineering - 10%	33.8	44.1	61.0	68.0	116.9	173.6	247.6	375.7
Inspection and testing - 5%	16.9	22.1	30.5	34.0	58.4	86.8	123.8	187.9
Construction and field expenses - 5%	16.9	22.1	30.5	34.0	58.4	86.8	123.8	187.9
Contractors fee - 10%	33.8	44.1	61.0	68.0	116.9	173.6	247.6	375.7
Start-up cost - 1%	3.4	4.4	6.1	6.8	11.7	17.4	24.8	37.6
Spare parts inventory - 1%	3.4	4.4	6.1	6.8	11.7	17.4	24.8	37.6
Interest during construction - 10%	33.8	44.1	61.0	68.0	116.9	173.6	247.6	375.7
Subtotal Indirect Capital	141.8	185.2	256.2	285.5	490.8	729.2	1039.7	1578.1
Working capital - 10%	48.0	62.6	86.6	96.5	165.9	246.5	351.5	533.6
Contingency - 15%	71.9	93.9	129.9	144.8	248.9	369.8	527.3	800.3
Total Indirect Capital	261.7	341.8	472.8	526.8	905.6	1345.6	1918.5	2912.0
TOTAL FACILITY COST	599.4	782.8	1082.8	1206.6	2074.1	3081.8	4394.0	6669.4

TABLE E-8

LANDFILL - INITIAL CAPITAL COSTS (YEAR 1) - DOUBLE SYNTHETIC/CLAY

DIRECT CAPITAL COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Land	100.6	151.9	202.7	233.2	314.0	484.7	622.8	954.2
Clearing & grubbing	23.7	42.3	61.9	74.0	107.0	179.7	240.3	389.3
Fence & gates					80.1	98.5	111.0	136.4
Roadways	5.0	7.4	9.5	10.6	25.0	29.6	34.6	40.9
Truck loading area	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Office building					67.0	67.0	89.3	89.3
Scale					41.5	41.5	41.5	41.5
Signs	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Maintenance building	14.3	14.3	20.6	20.6	28.1	28.1	36.6	36.6
Utilities site work					29.2	29.2	29.2	29.2
Surface water control	8.6	12.8	16.3	18.2	22.7	30.6	36.1	47.0
Leachate treatment system	63.0	63.0	63.0	63.0	63.0	63.0	85.0	110.0
Groundwater wells	10.0	10.0	12.0	12.0	14.0	16.0	18.0	22.0
Office equipment					10.3	11.9	13.5	15.1
Laboratory equipment					25.0	25.0	25.0	25.0
Portable pumps	3.4	3.4	6.7	6.7	6.7	10.1	10.1	10.1
Heavy equipment	65.0	65.0	108.0	108.0	120.0	216.0	476.0	703.0
First year cell construction	38.0	75.1	125.6	157.4	261.1	500.8	745.7	1354.5
Total Direct Capital	345.8	459.4	640.5	717.9	1228.9	1845.9	2628.9	4018.3
INDIRECT CAPITAL COSTS ($1000)								
Engineering - 10%	34.6	45.9	64.1	71.8	122.9	184.6	262.9	401.8
Inspection and testing - 5%	17.3	23.0	32.0	35.9	61.4	92.3	131.4	200.9
Construction and field expenses - 5%	17.3	23.0	32.0	35.9	61.4	92.3	131.4	200.9
Contractors fee - 10%	34.6	45.9	64.1	71.8	122.9	184.6	262.9	401.8
Start-up cost - 1%	3.5	4.6	6.4	7.2	12.3	18.5	26.3	40.2
Spare parts inventory - 1%	3.5	4.6	6.4	7.2	12.3	18.5	26.3	40.2
Interest during construction - 10%	34.6	45.9	64.1	71.8	122.9	184.6	262.9	401.8
Subtotal Indirect Capital	145.2	192.9	269.0	301.5	516.1	775.3	1104.1	1687.7
Working capital - 10%	49.1	65.2	91.0	101.9	174.5	262.1	373.3	570.6
Contingency - 15%	73.7	97.9	136.4	152.9	261.8	393.2	560.0	855.9
Total Indirect Capital	268.0	356.0	496.4	556.4	952.4	1430.6	2037.4	3114.2
TOTAL FACILITY COST	613.8	815.4	1136.9	1274.3	2181.3	3276.5	4666.3	7132.5

TABLE E-9

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - UNLINED

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	3.6	13.4	31.0	43.1	86.6	206.2	346.3	716.3
Inspection fee - 3%	0.1	0.4	0.9	1.3	2.7	6.2	10.4	21.5
Contractors fee - 10%	0.4	1.3	3.1	4.3	8.9	20.6	34.6	71.6
Subtotal	4.1	15.1	35.0	48.7	100.1	233.0	391.3	809.4
Contingency fee - 10%	0.4	1.5	3.5	4.9	10.0	23.3	39.1	80.9
TOTAL	4.5	16.7	38.5	53.6	110.1	256.3	430.5	890.4

TABLE E-10

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - SINGLE SYNTHETIC

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	41.1	84.3	141.4	178.6	296.6	579.6	863.9	1594.9
Engineering fee - 7%	2.9	5.9	9.9	12.5	20.8	40.6	60.5	111.6
Inspection fee - 5%	2.1	4.2	7.1	8.9	14.8	29.0	43.2	79.7
Contractors fee - 10%	4.1	8.4	14.1	17.9	29.7	58.0	86.4	159.5
Subtotal	50.1	102.8	172.5	217.9	361.9	707.1	1054.0	1945.8
Contingency fee - 15%	7.5	15.4	25.9	32.7	54.3	106.1	158.1	291.9
TOTAL	57.7	118.3	198.4	250.6	416.1	813.2	1212.1	2237.6

TABLE E-11

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - DOUBLE SYNTHETIC

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	48.4	101.5	170.5	215.0	355.0	686.7	1014.1	1851.7
Engineering fee - 7%	3.4	7.1	11.9	15.1	24.9	48.1	71.0	129.6
Inspection fee - 5%	2.4	5.1	8.5	10.8	17.8	34.3	50.7	92.6
Contractors fee - 10%	4.8	10.2	17.1	21.5	35.5	68.7	101.4	185.2
Subtotal	59.0	123.8	208.0	262.3	433.1	837.8	1237.2	2259.1
Contingency fee - 15%	8.9	18.6	31.2	39.3	65.0	125.7	185.6	338.9
TOTAL	67.9	142.4	239.2	301.6	498.1	963.4	1422.8	2597.9

TABLE E-12

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - SINGLE CLAY

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	43.9	88.4	147.6	185.5	306.6	593.9	883.0	1622.4
Engineering fee - 7%	3.1	6.2	10.3	13.0	21.5	41.6	61.8	113.6
Inspection fee - 5%	2.2	4.4	7.4	9.3	15.3	29.7	44.2	81.1
Contractors fee - 10%	4.4	8.8	14.8	18.6	30.7	59.4	88.3	162.2
Subtotal	53.6	107.8	180.1	226.3	374.1	724.6	1077.3	1979.3
Contingency fee - 15%	8.0	16.2	27.0	33.9	56.1	108.7	161.6	296.9
TOTAL	61.6	124.0	207.1	260.3	430.2	833.2	1238.8	2276.2

TABLE E-13

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - SINGLE SYNTHETIC/CLAY

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	48.5	99.5	166.5	204.4	344.9	665.1	982.7	1793.5
Engineering fee - 7%	3.4	7.0	11.7	14.3	24.1	46.6	68.8	125.5
Inspection fee - 5%	2.4	5.0	8.3	10.2	17.2	33.3	49.1	89.7
Contractors fee - 10%	4.9	10.0	16.7	20.4	34.5	66.5	98.3	179.4
Subtotal	59.2	121.4	203.1	249.4	420.8	811.4	1198.9	2188.1
Contingency fee - 15%	8.9	18.2	30.5	37.4	63.1	121.7	179.8	328.2
TOTAL	68.0	139.6	233.6	286.8	483.9	933.1	1378.7	2516.3

TABLE E-14

LANDFILL - ANNUAL CAPITAL COSTS (YEARS 2-20) - DOUBLE SYNTHETIC/CLAY

ANNUAL CAPITAL INVESTMENT ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Annual capital investment	58.5	120.9	200.8	251.7	410.5	781.9	1144.4	2065.2
Engineering fee - 7%	4.1	8.5	14.1	17.6	28.7	54.7	80.1	144.6
Inspection fee - 5%	2.9	6.0	10.0	12.6	20.5	39.1	57.2	103.3
Contractors fee - 10%	5.9	12.1	20.1	25.2	41.1	78.2	114.4	206.5
Subtotal	71.4	147.5	245.0	307.1	500.8	953.9	1396.2	2519.5
Contingency fee - 15%	10.7	22.1	36.7	46.1	75.1	143.1	209.4	377.9
TOTAL	82.1	169.6	281.7	353.1	575.9	1097.0	1605.6	2897.5

Final closure costs for landfills are presented in Tables E-15 through E-20. These costs are incurred in year 21 and include costs for closing both the final cell (the major portion of the costs) and the total landfill facility (e.g., decontaminating equipment, monitoring, and certifying closure). For all designs and sizes, cover is the major expense.

Tables E-21 and E-22 contain the operating and maintenance (O&M) costs associated with the technical aspects of operating the facility. These costs are incurred annually during years 1 through 20. To the costs reported in these two tables should be added 6 percent of the total facility cost for maintenance supplies (1 percent), insurance (2 percent), taxes (2 percent), and general and administration (1 percent). We did not include O&M costs for recordkeeping, reporting, monitoring, financial responsibility, etc. Thus, our costs understate the actual cost of disposing of hazardous waste.

1.2 Surface Impoundment Costs

The capital costs for surface impoundments appear in Tables E-23 through E-28. These costs are incurred during the first year of facility operation. As with landfills, it is necessary to excavate in building the unlined impoundment; additional capital expenses occur for building the berm. Unlike landfills, constructing the surface impoundments represents the major portion of the initial capital costs for the larger surface impoundments, those 5 acres and up. For the smaller surface impoundments, land and dredging equipment is a more significant expense.

Closure costs for surface impoundments are incurred in year 21. For this analysis, they are based on the assumption that the operator closes the impoundment by solidifying the remaining wastes and then placing a landfill cover over it. Solidifying the wastes is the major closure expense, ranging from about half the cost for the quarter acre impoundment to about 80 percent of the cost for the 11 acre impoundment. For impoundments of all sizes, most of the remaining cost is for cover. Tables E-29 through E-34 show the closure costs. It is also possible under Part 264 to close the surface impoundment by removing its wastes; the model provides the flexibility to estimate costs under this scenario.

TABLE E-15

LANDFILL - CLOSURE COSTS (YEAR 21) - UNLINED

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Cover	1.5	4.7	9.3	12.7	23.6	54.6	86.4	183.5
Inspection fee - 3%	.0	0.1	0.3	0.4	0.7	1.6	2.6	5.5
Contractors fee - 10%	0.2	0.5	0.9	1.3	2.4	5.5	8.6	18.4
Subtotal	1.7	5.3	10.5	14.4	26.7	61.7	97.6	207.4
Contingency fee - 10%	0.2	0.5	1.1	1.4	2.7	6.2	9.8	20.7
TOTAL	1.9	5.8	11.6	15.8	29.3	67.9	107.4	228.1

TABLE E-16

LANDFILL - CLOSURE COSTS (YEAR 21) - SINGLE SYNTHETIC

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Heavy equipment decontamination	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Cover	16.6	39.9	67.7	85.9	138.9	266.8	381.9	688.9
Engineering fee - 10%	1.7	4.0	6.8	8.6	13.9	26.7	38.2	68.9
Inspection fee - 5%	0.8	2.0	3.4	4.3	6.9	13.3	19.1	34.4
Contractors fee - 10% (fees on cover only)	1.7	4.0	6.8	8.6	13.9	26.7	38.2	68.9
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	28.6	57.7	92.4	115.2	181.4	341.4	485.4	869.1
Contingency fee - 15%	4.3	8.7	13.9	17.3	27.2	51.2	72.8	130.4
TOTAL	32.8	66.3	106.3	132.5	208.6	392.6	558.2	999.5

TABLE E-17

LANDFILL - CLOSURE COSTS (YEAR 21) - DOUBLE SYNTHETIC

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Heavy equipment decontamination	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Cover	16.7	40.0	67.8	86.0	139.0	267.0	382.1	689.2
Engineering fee - 10%	1.7	4.0	6.8	8.6	13.9	26.7	38.2	68.9
Inspection fee - 5%	0.8	2.0	3.4	4.3	7.0	13.4	19.1	34.5
Contractors fee - 10% (fees on cover only)	1.7	4.0	6.8	8.6	13.9	26.7	38.2	68.9
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	28.7	57.8	92.6	115.3	181.6	341.7	485.6	869.5
Contingency fee - 15%	4.3	8.7	13.9	17.3	27.2	51.2	72.8	130.4
TOTAL	33.0	66.5	106.4	132.6	208.8	392.9	558.5	999.9

TABLE E-18

LANDFILL - CLOSURE COSTS (YEAR 21) - SINGLE CLAY

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Heavy equipment decontamination	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Cover	18.6	42.8	71.4	90.2	144.2	274.0	390.4	700.0
Engineering fee - 10%	1.9	4.3	7.1	9.0	14.4	27.4	39.0	70.0
Inspection fee - 5%	0.9	2.1	3.6	4.5	7.2	13.7	19.5	35.0
Contractors fee - 10% (fees on cover only)	1.9	4.3	7.1	9.0	14.4	27.4	39.0	70.0
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	31.1	61.3	97.1	120.6	188.1	350.4	496.0	883.0
Contingency fee - 15%	4.7	9.2	14.6	18.1	28.2	52.6	74.4	132.5
TOTAL	35.7	70.5	111.6	138.6	216.3	403.0	570.4	1015.5

TABLE E-19

LANDFILL - CLOSURE COSTS (YEAR 21) - SINGLE SYNTHETIC/CLAY

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Heavy equipment decontamination	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Cover	18.6	42.8	71.4	90.2	144.2	274.0	390.4	700.0
Engineering fee - 10%	1.9	4.3	7.1	9.0	14.4	27.4	39.0	70.0
Inspection fee - 5%	0.9	2.1	3.6	4.5	7.2	13.7	19.5	35.0
Contractors fee - 10% (fees on cover only)	1.9	4.3	7.1	9.0	14.4	27.4	39.0	70.0
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	31.1	61.3	97.1	120.6	188.1	350.4	496.0	883.0
Contingency fee - 15%	4.7	9.2	14.6	18.1	28.2	52.6	74.4	132.5
TOTAL	35.7	70.5	111.6	138.6	216.3	403.0	570,4	1015.5

TABLE E-20

LANDFILL - CLOSURE COSTS (YEAR 21) - DOUBLE SYNTHETIC/CLAY

CLOSURE COST ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
Heavy equipment decontamination	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.3
Cover	20.5	45.8	75.2	94.4	149.4	281.0	396.6	710.7
Engineering fee - 10%	2.1	4.6	7.5	9.4	14.9	28.1	39.9	71.1
Inspection fee - 5%	1.0	2.3	3.8	4.7	7.5	14.1	19.9	35.5
Contractors fee - 10% (fees on cover only)	2.1	4.6	7.5	9.4	14.9	28.1	39.9	71.1
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	33.4	65.1	101.8	125.8	194.6	359.2	506.3	896.4
Contingency fee - 15%	5.0	9.8	15.3	18.9	29.2	53.9	75.9	134.5
TOTAL	38.4	74.8	117.1	144.7	223.7	413.0	582.2	1030.8

TABLE E-21

LANDFILL - OPERATING AND MAINTENANCE COSTS (YEARS 1-20) - UNLINED

DIRECT O&M COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
1. Operating Labor								
-receiving clerks								
@ $15,000/yr					15.0	15.0	15.0	15.0
-operators								
@ $18,000/yr	9.0	13.5	18.0	27.0	36.0	45.0	54.0	63.0
-clerical staff								
@ $13,000/yr					13.0	19.5	26.0	32.5
-security								
@ $12,000/yr					12.0	12.0	12.0	12.0
2. Supervisory Labor								
-manager					30.0	30.0	30.0	35.0
-engineer					25.0	25.0	25.0	25.0
3. Mechanic								
@ $17,000/yr	4.3	8.5	12.8	12.8	17.0	25.5	25.5	34.0
4. Total Direct Labor	13.3	22.0	30.8	39.8	148.0	172.0	187.5	216.5
5. Utilities								
-fuel	2.6	5.2	13.0	19.5	26.0	32.5	46.8	58.5
-electricity	0.5	0.5	1.0	1.0	1.5	1.5	2.0	2.0
-heating	1.0	1.0	1.5	1.5	3.0	3.0	3.5	3.5
Total Direct O&M	17.4	28.7	46.3	61.8	178.5	209.0	239.8	280.5

INDIRECT O&M COSTS ($1000)								
1. Fringe Benefits								
@ 25% direct labor	3.3	5.5	7.7	10.0	37.0	43.0	46.9	54.1
2. Plant Overhead								
@ 50% direct labor	6.7	11.0	15.4	19.9	74.0	86.0	93.8	108.3
Total Indirect O&M	10.0	16.5	23.1	29.9	111.0	129.0	140.6	162.4
TOTAL O&M	27.4	45.2	69.4	91.7	289.5	338.0	380.4	442.9

TABLE E-22

LANDFILL - OPERATING AND MAINTENANCE COSTS (YEARS 1-20) - ALL DESIGNS

DIRECT O&M COSTS ($1000)	500 MT	2000 MT	5000 MT	7000 MT	15,000 MT	35,000 MT	60,000 MT	123,000 MT
1. Operating Labor								
-receiving clerks @ $15,000/yr					15.0	15.0	15.0	15.0
-operators @ $18,000/yr	9.0	13.5	18.0	27.0	36.0	45.0	54.0	63.0
-clerical staff @ $13,000/yr					13.0	19.5	26.0	32.5
-security @ $12,000/yr					12.0	12.0	12.0	12.0
2. Supervisory Labor								
-manager					30.0	30.0	30.0	35.0
-engineer					25.0	25.0	25.0	25.0
3. Mechanic @ $17,000/yr	4.3	8.5	12.8	12.8	17.0	25.5	25.5	34.0
4. Laboratory Staff								
-chemist @ $20,000/yr					20.0	20.0	20.0	20.0
-technician @ $13,000/yr					6.5	6.5	13.0	26.0
5. Total Direct Labor	13.3	22.0	30.8	39.8	174.5	198.5	220.5	262.5
6. Laboratory Supplies @ $400-700/mo					4.8	6.0	7.2	8.4
7. Leachate Treatment @ $0.15/gal	6.4	24.3	57.7	79.9	166.2	381.0	642.7	1303.0
8. Utilities								
-fuel	2.6	5.2	13.0	19.5	26.0	32.5	46.8	58.5
-electricity	0.5	0.5	1.0	1.0	1.5	1.5	2.0	2.0
-heating	1.0	1.0	1.5	1.5	3.0	3.0	3.5	3.5
Total Direct O&M	23.8	53.0	104.0	141.7	376.0	622.5	922.7	1637.9
INDIRECT O&M COSTS ($1000)								
1. Fringe Benefits @ 25% direct labor	3.3	5.5	7.7	10.0	43.6	49.6	55.1	65.6
2. Plant Overhead @ 50% direct labor	6.7	11.0	15.4	19.9	87.3	99.3	110.3	131.3
Total Indirect O&M	10.0	16.5	23.1	29.9	130.9	148.9	165.4	196.9
TOTAL O&M	33.8	69.5	127.1	171.6	506.9	771.4	1088.1	1834.8

TABLE E-23

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - UNLINED

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	9.5	19.9	44.0	101.0	318.7	894.1
Total Direct Capital	206.4	224.7	266.1	342.6	611.8	1263.5

INDIRECT CAPITAL COSTS ($1000)						
Engineering - 5%	10.3	11.2	13.3	17.1	30.6	63.2
Inspection - 3%	6.2	6.7	8.0	10.3	18.4	37.9
Construction and field expenses - 5%	10.3	11.2	13.3	17.1	30.6	63.2
Contractors fee - 10%	20.6	22.5	26.6	34.3	61.2	126.4
Start-up cost - 1%	2.1	2.2	2.7	3.4	6.1	12.6
Spare parts inventory - 1%	2.1	2.2	2.7	3.4	6.1	12.6
Interest during construction - 10%	20.6	22.5	26.6	34.3	61.2	126.4
Subtotal Indirect Capital	72.2	78.6	93.1	119.9	214.1	442.2
Working capital - 10%	27.9	30.3	35.9	46.3	82.6	170.6
Contingency - 10%	27.9	30.3	35.9	46.3	82.6	170.6
Total Indirect Capital	128.0	139.3	165.0	212.4	379.3	783.4
TOTAL FACILITY COST	334.4	364.0	431.1	555.0	991.1	2046.9

TABLE E-24

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE SYNTHETIC

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Signs	0.8	0.8	0.8	0.8	0.8	0.8
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Groundwater wells	10.0	10.0	10.0	12.0	12.0	14.0
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	16.0	32.0	66.9	144.9	424.6	1122.4
Total Direct Capital	223.7	247.6	299.8	399.3	730.5	1506.6

INDIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Engineering - 10%	22.4	24.8	30.0	39.9	73.1	150.7
Inspection - 5%	11.2	12.4	15.0	20.0	36.5	75.3
Construction and field expenses - 5%	11.2	12.4	15.0	20.0	36.5	75.3
Contractors fee - 10%	22.4	24.8	30.0	39.9	73.1	150.7
Start-up cost - 1%	2.2	2.5	3.0	4.0	7.3	15.1
Spare parts inventory - 1%	2.2	2.5	3.0	4.0	7.3	15.1
Interest during construction - 10%	22.4	24.8	30.0	39.9	73.1	150.7
Subtotal Indirect Capital	94.0	104.0	125.9	167.7	306.8	632.8
Working capital - 10%	31.8	35.2	42.6	56.7	103.7	213.9
Contingency - 15%	47.6	52.7	63.9	85.1	155.6	320.9
Total Indirect Capital	173.4	191.9	232.3	309.5	566.1	1167.6
TOTAL FACILITY COST	397.1	439.5	532.1	708.8	1296.6	2674.2

TABLE E-25

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - DOUBLE SYNTHETIC

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Signs	0.8	0.8	0.8	0.8	0.8	0.8
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Groundwater wells	10.0	10.0	10.0	12.0	12.0	14.0
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	45.3	74.6	135.5	264.7	694.3	1688.1
Total Direct Capital	253.0	290.2	368.4	519.1	1000.2	2072.3

INDIRECT CAPITAL COSTS ($1000)						
Engineering - 10%	25.3	29.0	36.8	51.9	100.0	207.2
Inspection - 5%	12.7	14.5	18.4	26.0	50.0	103.6
Construction and field expenses - 5%	12.7	14.5	18.4	26.0	50.0	103.6
Contractors fee - 10%	25.3	29.0	36.8	51.9	100.0	207.2
Start-up cost - 1%	2.5	2.9	3.7	5.2	10.0	20.7
Spare parts inventory - 1%	2.5	2.9	3.7	5.2	10.0	20.7
Interest during construction - 10%	25.3	29.0	36.8	51.9	100.0	207.2
Subtotal Indirect Capital	106.3	121.9	154.7	218.0	420.1	870.4
Working capital - 10%	35.9	41.2	52.3	73.7	142.0	294.3
Contingency - 15%	53.9	61.8	78.5	110.6	213.0	441.4
Total Indirect Capital	196.1	224.9	285.5	402.3	775.2	1606.0
TOTAL FACILITY COST	449.1	515.1	653.9	921.4	1775.4	3678.3

TABLE E-26

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE CLAY

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Signs	0.8	0.8	0.8	0.8	0.8	0.8
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Groundwater wells	10.0	10.0	10.0	12.0	12.0	14.0
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	18.8	37.2	76.9	164.5	472.9	1228.2
Total Direct Capital	226.5	252.8	309.8	418.9	778.8	1612.4

INDIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Engineering - 10%	22.7	25.3	31.0	41.9	77.9	161.2
Inspection - 5%	11.3	12.6	15.5	20.9	38.9	80.6
Construction and field expenses - 5%	11.3	12.6	15.5	20.9	38.9	80.6
Contractors fee - 10%	22.7	25.3	31.0	41.9	77.9	161.2
Start-up cost - 1%	2.3	2.5	3.1	4.2	7.8	16.1
Spare parts inventory - 1%	2.3	2.5	3.1	4.2	7.8	16.1
Interest during construction - 10%	22.7	25.3	31.0	41.9	77.9	161.2
Subtotal Indirect Capital	95.1	106.2	130.1	175.9	327.1	677.2
Working capital - 10%	32.2	35.9	44.0	59.5	110.6	229.0
Contingency - 15%	48.2	53.8	66.0	89.2	165.9	343.4
Total Indirect Capital	175.5	195.9	240.1	324.6	603.6	1249.6
TOTAL FACILITY COST	402.0	448.7	549.9	743.5	1382.4	2862.0

TABLE E-27

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - SINGLE SYNTHETIC/CLAY

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Signs	0.8	0.8	0.8	0.8	0.8	0.8
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Groundwater wells	10.0	10.0	10.0	12.0	12.0	14.0
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	46.1	75.7	137.5	268.7	704.6	1711.6
Total Direct Capital	253.8	291.3	370.4	523.1	1010.5	2095.8

INDIRECT CAPITAL COSTS ($1000)						
Engineering - 10%	25.4	29.1	37.0	52.3	101.1	209.6
Inspection - 5%	12.7	14.6	18.5	26.2	50.5	104.8
Construction and field expenses - 5%	12.7	14.6	18.5	26.2	50.5	104.8
Contractors fee - 10%	25.4	29.1	37.0	52.3	101.1	209.6
Start-up cost - 1%	2.5	2.9	3.7	5.2	10.1	21.0
Spare parts inventory - 1%	2.5	2.9	3.7	5.2	10.1	21.0
Interest during construction - 10%	25.4	29.1	37.0	52.3	101.1	209.6
Subtotal Indirect Capital	106.6	122.3	155.6	219.7	424.4	880.2
Working capital - 10%	36.0	41.4	52.6	74.3	143.5	297.6
Contingency - 15%	54.1	62.0	78.9	111.4	215.2	446.4
Total Indirect Capital	196.7	225.8	287.1	405.4	783.1	1624.2
TOTAL FACILITY COST	450.5	517.1	657.5	928.5	1793.6	3720.0

TABLE E-28

SURFACE IMPOUNDMENT - INITIAL CAPITAL COSTS (YEAR 1) - DOUBLE SYNTHETIC/CLAY

DIRECT CAPITAL COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Land	41.7	47.9	57.4	72.3	106.9	162.7
Clearing & grubbing	5.4	7.1	9.7	14.3	25.9	46.4
Signs	0.8	0.8	0.8	0.8	0.8	0.8
Utilities site work	8.5	8.5	8.5	8.5	8.5	8.5
Groundwater wells	10.0	10.0	10.0	12.0	12.0	14.0
Portable pumps	5.3	5.3	10.5	10.5	15.8	15.8
Dredging equipment	130.0	130.0	130.0	130.0	130.0	130.0
Inlet/outlet structures	6.0	6.0	6.0	6.0	6.0	6.0
Impoundment construction	55.7	93.2	170.2	330.8	852.5	2028.0
Total Direct Capital	263.4	308.8	403.1	585.2	1158.4	2412.2
INDIRECT CAPITAL COSTS ($1000)						
Engineering - 10%	26.3	30.9	40.3	58.5	115.8	241.2
Inspection - 5%	13.2	15.4	20.2	29.3	57.9	120.6
Construction and field expenses - 5%	13.2	15.4	20.2	29.3	57.9	120.6
Contractors fee - 10%	26.3	30.9	40.3	58.5	115.8	241.2
Start-up cost - 1%	2.6	3.1	4.0	5.9	11.6	24.1
Spare parts inventory - 1%	2.6	3.1	4.0	5.9	11.6	24.1
Interest during construction - 10%	26.3	30.9	40.3	58.5	115.8	241.2
Subtotal Indirect Capital	110.6	129.7	169.3	245.8	486.5	1013.1
Working capital - 10%	37.4	43.8	57.2	83.1	164.5	342.5
Contingency - 15%	56.1	65.8	85.9	124.6	246.7	513.8
Total Indirect Capital	204.1	239.3	312.4	453.5	897.8	1869.5
TOTAL FACILITY COST	467.5	548.1	715.5	1038.7	2056.2	4281.7

TABLE E-29

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - UNLINED

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Cover	11.0	25.2	58.8	140.3	459.0	1316.9
Inspection fee - 3%	0.3	0.8	1.8	4.2	13.8	39.5
Contractors fee - 10%	1.1	2.5	5.9	14.0	45.9	131.7
Subtotal	12.4	28.5	66.4	158.5	518.7	1488.1
Contingency fee - 10%	1.2	2.8	6.6	15.9	51.9	148.8
TOTAL	13.7	31.3	73.1	174.4	570.5	1636.9

TABLE E-30

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - SINGLE SYNTHETIC

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Solidification	62.4	148.7	354.9	854.5	2759.2	7971.5
Equipment decontamination	0.3	0.3	0.3	0.3	0.3	0.3
Cover	43.1	81.6	161.2	331.2	906.3	2264.4
Engineering fee - 10%	4.3	8.2	16.1	33.1	90.6	226.4
Inspection fee - 5%	2.2	4.1	8.1	16.6	45.3	113.2
Contractors fee - 10% (fees on cover only)	4.3	8.2	16.1	33.1	90.6	226.4
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	124.3	258.7	564.4	1276.5	3900.1	10810.0
Contingency fee - 15%	18.6	38.8	84.7	191.5	585.0	1621.5
TOTAL	142.9	297.5	649.1	1468.0	4485.1	12431.5

TABLE E-31

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - DOUBLE SYNTHETIC

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Solidification	62.4	148.7	354.9	854.5	2759.2	7971.5
Equipment decontamination	0.3	0.3	0.3	0.3	0.3	0.3
Cover	43.1	81.6	161.2	331.2	906.3	2264.4
Engineering fee - 10%	4.3	8.2	16.1	33.1	90.6	226.4
Inspection fee - 5%	2.2	4.1	8.1	16.6	45.3	113.2
Contractors fee - 10% (fees on cover only)	4.3	8.2	16.1	33.1	90.6	226.4
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	124.3	258.7	564.4	1276.5	3900.1	10810.0
Contingency fee - 15%	18.6	38.8	84.7	191.5	585.0	1621.5
TOTAL	142.9	297.5	649.1	1468.0	4485.1	12431.5

TABLE E-32

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - SINGLE CLAY

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Solidification	62.4	148.7	354.9	854.5	2759.2	7971.5
Equipment decontamination	0.3	0.3	0.3	0.3	0.3	0.3
Cover	43.1	81.6	161.2	331.2	906.3	2264.4
Engineering fee - 10%	4.3	8.2	16.1	33.1	90.6	226.4
Inspection fee - 5%	2.2	4.1	8.1	16.6	45.3	113.2
Contractors fee - 10% (fees on cover only)	4.3	8.2	16.1	33.1	90.6	226.4
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	124.3	258.7	564.4	1276.5	3900.1	10810.0
Contingency fee - 15%	18.6	38.8	84.7	191.5	585.0	1621.5
TOTAL	142.9	297.5	649.1	1468.0	4485.1	12431.5

TABLE E-33

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - SINGLE SYNTHETIC/CLAY

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Solidification	62.4	148.7	354.9	854.5	2759.2	7971.5
Equipment decontamination	0.3	0.3	0.3	0.3	0.3	0.3
Cover	44.5	83.4	163.8	334.7	911.6	2272.1
Engineering fee - 10%	4.5	8.3	16.4	33.5	91.2	227.2
Inspection fee - 5%	2.2	4.2	8.2	16.7	45.6	113.6
Contractors fee - 10% (fees on cover only)	4.5	8.3	16.4	33.5	91.2	227.2
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	126.0	261.0	567.7	1280.9	3906.7	10819.6
Contingency fee - 15%	18.9	39.1	85.1	192.1	586.0	1622.9
TOTAL	144.9	300.1	652.8	1473.0	4492.7	12442.6

TABLE E-34

SURFACE IMPOUNDMENT - CLOSURE COSTS (YEAR 21) - DOUBLE SYNTHETIC/CLAY

CLOSURE COST ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
Solidification	62.4	148.7	354.9	854.5	2759.2	7971.5
Equipment decontamination	0.3	0.3	0.3	0.3	0.3	0.3
Cover	44.5	83.4	163.8	334.7	911.6	2272.1
Engineering fee - 10%	4.5	8.3	16.4	33.5	91.2	227.2
Inspection fee - 5%	2.2	4.2	8.2	16.7	45.6	113.6
Contractors fee - 10% (fees on cover only)	4.5	8.3	16.4	33.5	91.2	227.2
Monitoring	1.3	1.3	1.3	1.3	1.3	1.3
Certification and supervision	6.4	6.4	6.4	6.4	6.4	6.4
Subtotal	126.0	261.0	567.7	1280.9	3906.7	10819.6
Contingency fee - 15%	18.9	39.1	85.1	192.1	586.0	1622.9
TOTAL	144.9	300.1	652.8	1473.0	4492.7	12442.6

O&M costs for surface impoundments appear in Tables E-35 and E-36. These costs are incurred annually during the 20 years of impoundment operating life. Six percent of the total facility costs should also be added to the costs reported in these two tables for maintenance supplies, insurance, taxes, and G&A. O&M costs are relatively minor.

1.3 Surface Impoundment Dredging

In order for a surface impoundment to perform during its operating life, it is necessary to dredge settled solids from the impoundment. We used the dredging component of the Facilities Design Computer Cost Model to estimate the frequency of surface impoundment dredging and the quantity of sludge removed at each dredging. We assumed that an operator would dredge the impoundment when the depth of settled sludge was equal to one-half of the operating depth. Several assumptions underlie our estimate of dredging costs:

- the dredge has a sludge removal capacity of 110 MT/hr;
- the labor cost for the dredge operator is $11/hr;
- fuel, lubricants, and spare parts for the dredge are $12/hr:
- the dredged sludge has a weight of 1.2 MT/m^3; and
- transportation (250 mile one-way haul) and disposal of dredged material costs $150/MT.

Table E-37 summarizes the results of the surface impoundment dredging calculations. As the table shows, dredging costs are significant, ranging from about one-fourth of initial capital costs for a double synthetic/clay lined quarter acre impoundment, to over four times the initial capital for an 11 acre unlined impoundment.

1.4 Other Cost Assumptions

Several other assumptions are inherent in our cost estimates. We assumed that on-site clay is used in all facility designs requiring clay. If it is necessary to transport clay from off-site, costs will be from 12 percent

TABLE E-35

SURFACE IMPOUNDMENT - OPERATING AND MAINTENANCE COSTS (YEARS 1-20) - UNLINED

DIRECT O&M COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
1. Operating Labor @ $18,000/yr	4.5	4.5	9.0	9.0	13.5	13.5
2. Maintenance Labor @ $17,000/yr	4.3	4.3	8.5	8.5	12.8	12.8
3. Total Direct Labor	8.8	8.8	17.5	17.5	26.3	26.3
4. Utilities (electricity and fuel)	0.5	0.5	1.0	1.0	1.5	1.5
Total Direct O&M	9.3	9.3	18.5	18.5	27.8	27.8

INDIRECT O&M COSTS ($1000)						
1. Fringe Benefits @ 25% direct labor	2.2	2.2	4.4	4.4	6.6	6.6
2. Plant Overhead @ 50% direct labor	4.4	4.4	8.8	8.8	13.2	13.2
Total Indirect O&M	6.6	6.6	13.1	13.	19.7	19.7
TOTAL O&M	15.9	15.9	31.6	31.6	47.5	47.5

TABLE E-36

SURFACE IMPOUNDMENT - OPERATING AND MAINTENANCE COSTS (YEARS 1-20) - ALL DESIGNS

DIRECT O&M COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
1. Operating Labor @ $18,000/yr	4.5	4.5	9.0	9.0	13.5	13.5
2. Maintenance Labor @ $17,000/yr	4.3	4.3	8.5	8.5	12.8	12.8
3. Total Direct Labor	8.8	8.8	17.5	17.5	26.3	26.3
4. Utilities (electricity and fuel)	0.5	0.5	1.0	1.0	1.5	1.5
Total Direct O&M	9.3	9.3	18.5	18.5	27.8	27.8

INDIRECT O&M COSTS ($1000)	0.25 ac	0.50 ac	1.00 ac	2.00 ac	5.00 ac	11.00 ac
1. Fringe Benefits @ 25% direct labor	2.2	2.2	4.4	4.4	6.6	6.6
2. Plant Overhead @ 50% direct labor	4.4	4.4	8.8	8.8	13.2	13.2
Total Indirect O&M	6.6	6.6	13.1	13.1	19.7	19.7
TOTAL O&M	15.9	15.9	31.6	31.6	47.5	47.5

Table E-37. Surface Impoundment Dredging Quantities and Costs

Impoundment Size (acre)	Sludge Quantity Removed/Dredging (M^3)	Cost for One Dredging ($)	Time to First Dredging (yrs)	Time Between Dredgings (yr)	Number of Dredgings/ 20 Year Period
0.25	617	111,215	7.56	7.56	2
0.50	1556	280,470	9.53	9.53	2
1.00	3623	653,049	8.88	8.88	2
2.00	8030	1,447,415	9.84	9.84	2
5.00	21,906	3,948,576	13.42	13.42	1
11.00	50,550	9,111,684	12.39	12.39	1

to 53 percent more than those we show here, depending on the size of the facility. For landfills, we assumed that the smaller landfills, up to and including 7000 MT per year, are on-site, and will not require the fences and gates, office buildings, scales, and office and laboratory equipment that the larger landfills will require. Finally, we assumed that all surface impoundments are on-site.

2.0 ECONOMIC COSTS

This section of the appendix describes how we transformed the engineering costs for the liner designs described in the previous section into economic costs, discusses the results, and notes the limitations of the analysis.

2.1 Methodology

We calculated the present values (PV) of costs (disregarding tax consequences) for each landfill and surface impoundment design scenario and size, for each year of the facility's operating life. We then calculated the total present value (TPV) for each design and size. Finally we annualized these present values, and also calculated the annualized present value on a per ton basis for landfills and on a per gallon basis for surface impoundments.

To calculate present values, we divided the cost each year by a discount factor:

$$PV_{\text{year } i} = \frac{\text{cost}_{\text{year } i}}{\text{discount factor}}$$

Our analysis did not consider inflation, taxes, or depreciation, so the discount factor [(inflation rate + 1) * (real rate of return + 1)] is equivalent to the real rate of return plus one.

In calculating the present values, we used a 3 percent real rate of return rather than the 10 percent rate OMB guidelines require. This rate is about the midpoint of the range of rates for the consumption rate of interest and the social rate of time preference. [1]

We used standard EPA assumptions of facility operating lives to assign the engineering costs Pope-Reid estimated to each year of the facility's operation. We assumed both landfills and surface impoundments operate 20 years, with the first cell in a landfill lined in year 1 and covered in year 2; a new cell lined in year 2 and covered the third year, and so on, with the last cell covered in year 21. Surface impoundments are lined in the first year and covered in year 21. We assigned capital costs to the first year, annual capital costs to years 2 through 20 (for landfills only), operating and maintenance costs to years 1 through 20, and closure costs to the twenty-first year.

To avoid double-counting finance costs in calculating present values, we excluded interest during construction and working capital from the initial indirect capital cost. For double synthetic and double synthetic/clay lined facilities, we also excluded the direct capital cost of ground water wells since Part 264 exempts double lined facilities from ground water monitoring.

We found the total present values of the total costs by summing up the present value over all years of the facility's life:

$$TPV = \sum_{\text{year } i} PV$$

In order to spread these costs evenly over the life of the facility, we annualized the total present values (APV) by multiplying them by a capital recovery factor (CRF):

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[1] See Guidelines for Preparing Regulatory Impact Analyses, Appendix C: Analysis of the Choice of Discount Rates. USEPA, July, 1984.

APV = TPV * CRF,

$$\text{where CRF} = \frac{\text{real rate of return} * (\text{real rate of return} + 1)^{OL}}{(\text{real rate of return} + 1)^{OL} - 1}$$

and OL = years of operating life.

With a 3 percent real rate of return and facility life of 20 years, the capital recovery factor is 0.0672. Finally, to derive annual unit costs, we divided the APV by facility capacity.

Calculating cost/risk and cost/effectiveness ratios requires incremental costs, rather than total cost. Whenever we calculate these ratios, we compute incremental costs from the total costs. Because the risks from the different designs are not ordered the same under all sets of technical assumptions, it is not possible to calculate incremental costs that apply to all scenarios.

2.2 Results

The total present values of total costs for landfills and surface impoundments are presented by facility design and size in Tables E-38 and E-39, and annualized in Tables E-40 and E-41. Tables E-42 and E-43 provide annual present values of total costs per unit of capacity. Graphs of these tables appear in Figures E-1 through E-6.

The results of per unit cost annualization indicate there are returns to scale for both landfills and surface impoundments. As the landfill model size increases for example, the annual cost per metric ton for the double synthetic/ clay liner design decreases from $312 for the smallest facility to $43 for the largest (Table E-42). And for surface impoundments 1/, all

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1/ Returns to scale for surface impoundments are demonstrated by the annual present value per gallon, rather than per acre, because the depth of an impoundment increases at a greater rate than the land area as acreage is increased.

TABLE E-38

LANDFILL TOTAL COSTS
PRESENT VALUE
(Thousands of Dollars)

LINER DESIGN:

MT/YEAR	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
500	$1,943	$2,098	$2,006	$2,110	$2,326	$850
2,000	3,580	3,962	3,642	3,926	4,041	1,429
5,000	5,952	6,603	6,091	6,524	7,292	2,340
7,000	7,539	8,357	7,694	8,135	9,192	2,989
15,000	15,947	17,269	16,174	17,051	18,532	6,075
35,000	26,957	29,391	27,279	28,910	31,561	11,951
60,000	39,055	42,477	39,478	41,772	45,390	16,364
123,000	68,163	74,009	68,785	72,706	78,896	26,228

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TABLE E-39

SURFACE IMPOUNDMENT TOTAL COSTS
PRESENT VALUE
(Thousands of Dollars)

LINER DESIGN:

ACRES	GALLONS *	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
0.25	638,307	$964	$999	$969	$1,014	$1,018	$779
0.50	1,430,379	1,440	1,497	1,449	1,512	1,529	1,092
1	3,272,381	2,827	2,926	2,844	2,944	2,985	2,117
2	7,677,124	5,198	5,376	5,229	5,400	5,487	3,657
5	29,560,545	10,977	11,397	11,055	11,433	11,657	6,440
11	80,951,673	27,311	29,205	27,482	28,266	28,760	15,002

---

* Gallon equivalents to acreage provided by Pope-Reid Associates.

TABLE E-40

LANDFILL TOTAL COSTS
ANNUALIZED PRESENT VALUE
(Thousands of Dollars)

LINER DESIGN:

MT/YEAR	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
500	$131	$141	$135	$142	$156	$57
2,000	241	266	245	264	296	96
5,000	400	444	409	438	490	157
7,000	507	562	517	547	618	201
15,000	1,072	1,161	1,087	1,146	1,246	408
35,000	1,812	1,976	1,834	1,943	2,121	803
60,000	2,625	2,855	2,654	2,808	3,051	1,100
123,000	4,582	4,975	4,623	4,887	5,303	1,763

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TABLE E-41

SURFACE IMPOUNDMENT TOTAL COSTS
ANNUALIZED PRESENT VALUE
(Thousands of Dollars)

LINER DESIGN:

ACRES	GALLONS *	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
0.25	638,307	$65	$67	$65	$68	$68	$52
0.50	1,430,379	97	101	97	102	103	73
1	3,272,381	190	197	191	198	201	142
2	7,677,124	349	361	352	363	369	246
5	29,560,545	738	766	743	768	784	433
11	80,951,673	1,836	1,896	1,847	1,900	1,933	1,008

---

* Gallon equivalents to acreage provided by Pope-Reid Associates.

TABLE E-42

LANDFILL TOTAL COSTS
ANNUALIZED PRESENT VALUE/MT

	LINER DESIGN:					
MT/YEAR	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
500	$262	$282	$270	$284	$312	$114
2,000	121	133	123	132	148	48
5,000	80	89	82	88	98	31
7,000	72	80	74	78	88	29
15,000	71	77	72	76	83	27
35,000	52	56	52	56	61	23
60,000	44	48	44	47	51	18
123,000	37	40	38	40	43	14

TABLE E-43

SURFACE IMPOUNDMENT TOTAL COSTS
ANNUALIZED PRESENT VALUE/GALLON

LINER DESIGN:

ACRES	GALLONS *	Single Synthetic	Double Synthetic	Single Clay	Single Synthetic /Clay	Double Synthetic /Clay	Baseline (Unlined)
0.25	638,307	$0.10	$0.10	$0.10	$0.11	$0.11	$0.08
0.50	1,430,379	0.07	0.07	0.07	0.07	0.07	0.05
1	3,272,381	0.06	0.06	0.06	0.06	0.06	0.04
2	7,677,124	0.05	0.05	0.05	0.05	0.05	0.03
5	29,560,545	0.02	0.03	0.03	0.03	0.03	0.01
11	80,951,673	0.02	0.02	0.02	0.02	0.02	0.01

---

* Gallon equivalents to acreage provided by Pope-Reid Associates.

KEY TO FIGURES

U	Unlined
S	Single Synthetic
SS	Double Synthetic
C	Single Clay
S/C	Single Synthetic/Clay
SS/C	Double Synthetic/Clay

FIGURE E-1

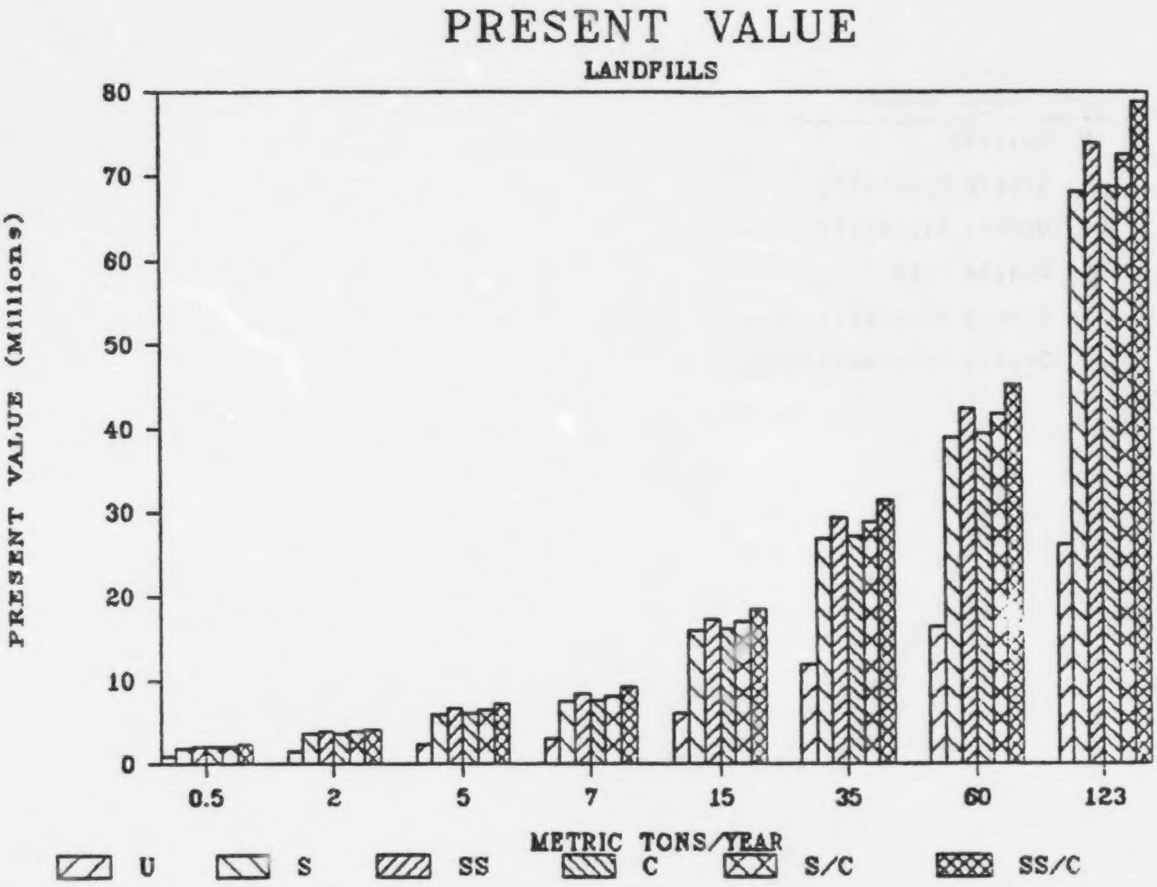

PRESENT VALUE
LANDFILLS
PRESENT VALUE (Millions)
80
70
60
50
40
30
20
10
0
0.5
2
5
7
15
35
60
123
METRIC TONS/YEAR
U
S
SS
C
S/C
SS/C

FIGURE E-2

PRESENT VALUE

SURFACE IMPOUNDMENTS

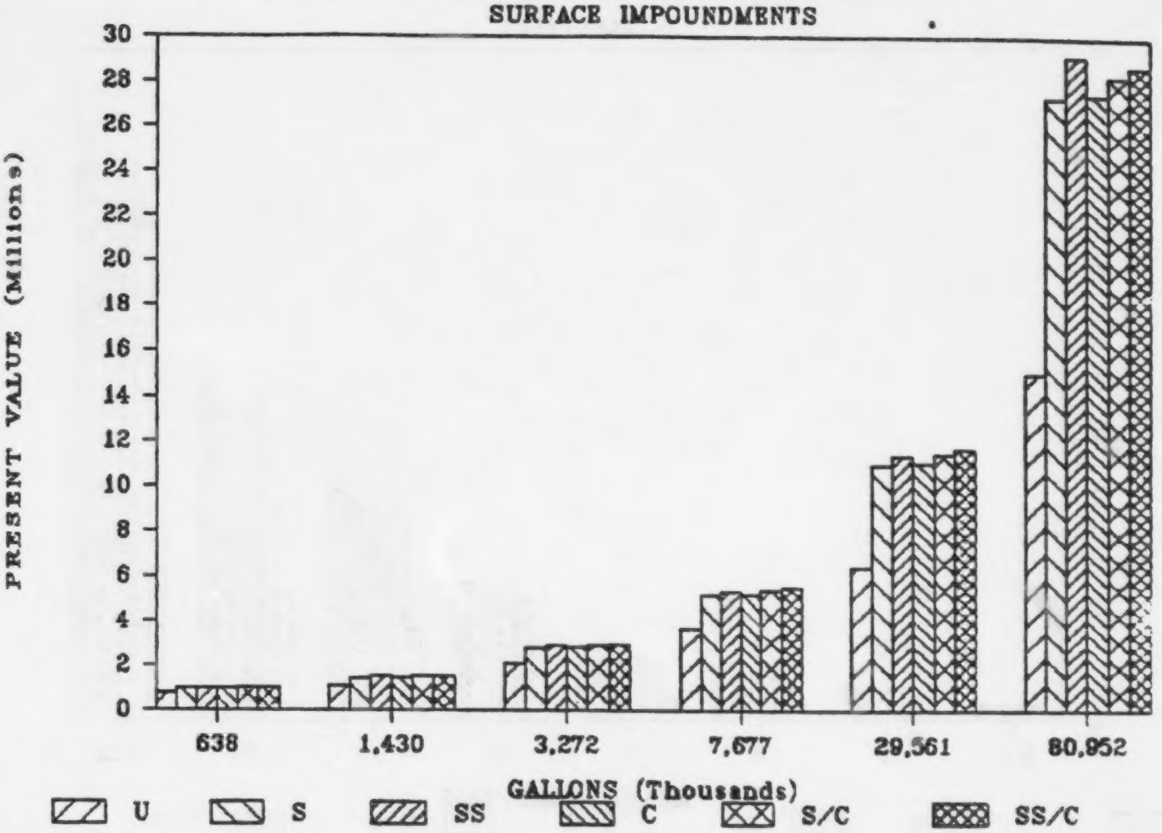


FIGURE E-3

ANNUALIZED PRESENT VALUE

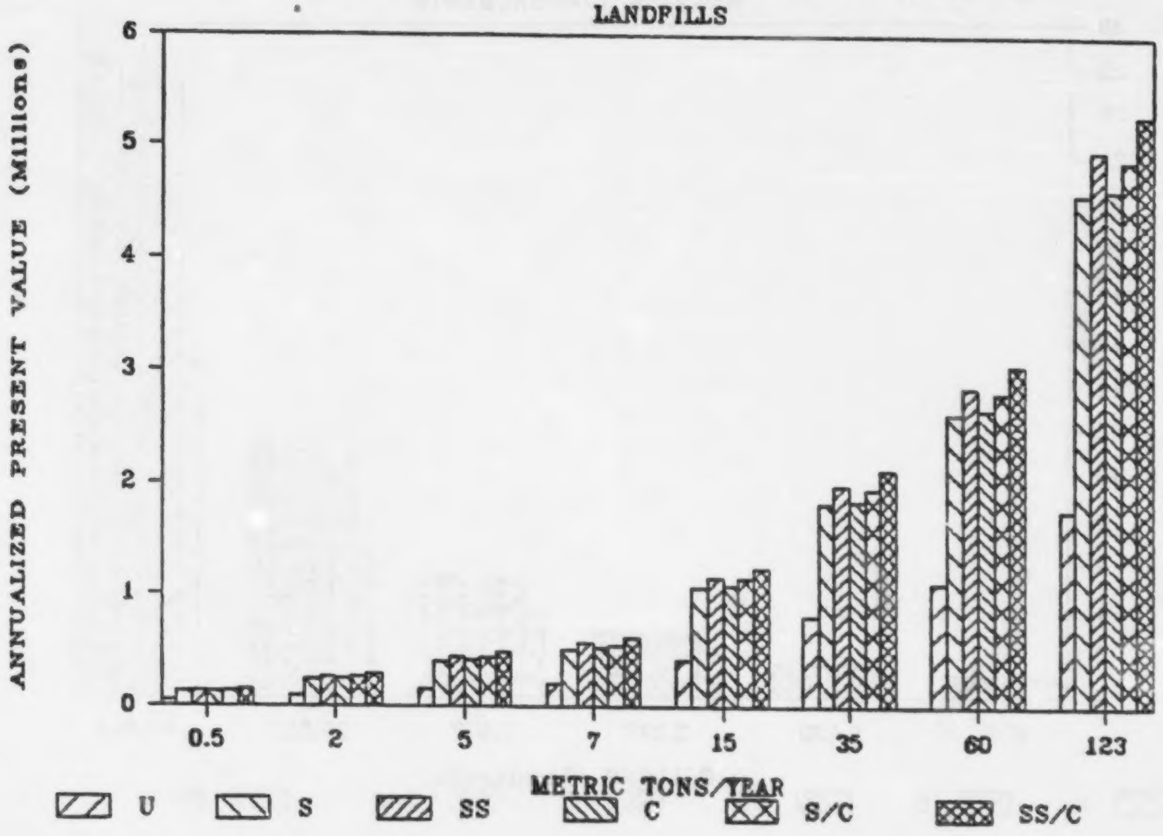


FIGURE E-4

ANNUALIZED PRESENT VALUE

SURFACE IMPOUNDMENTS

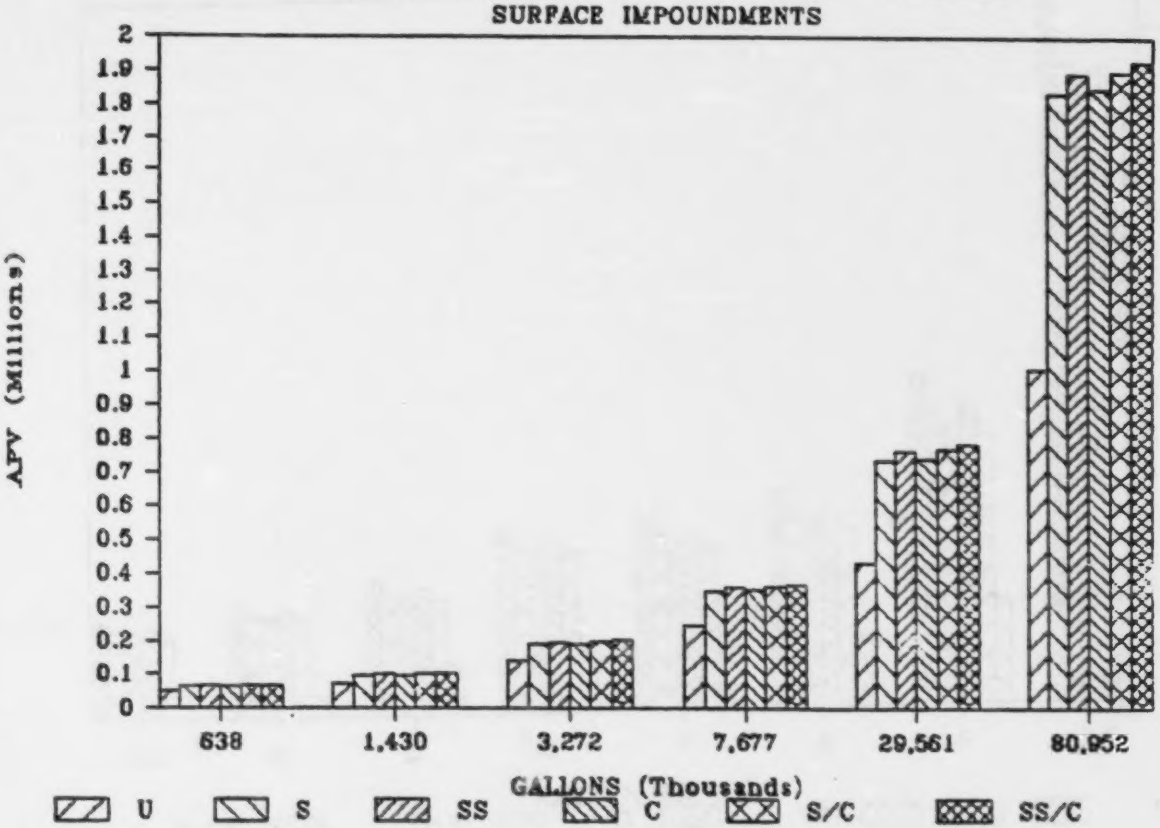


FIGURE E-5

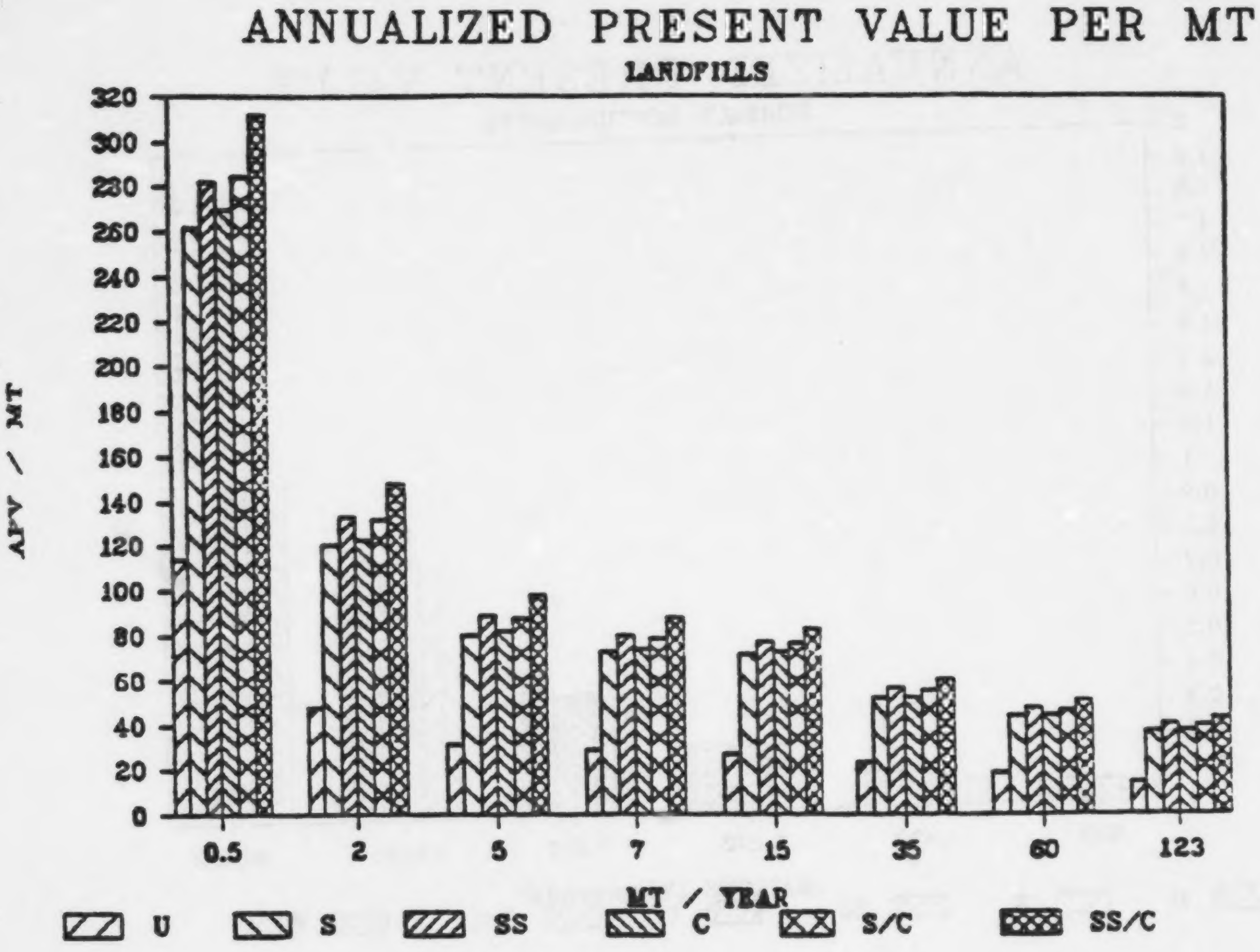
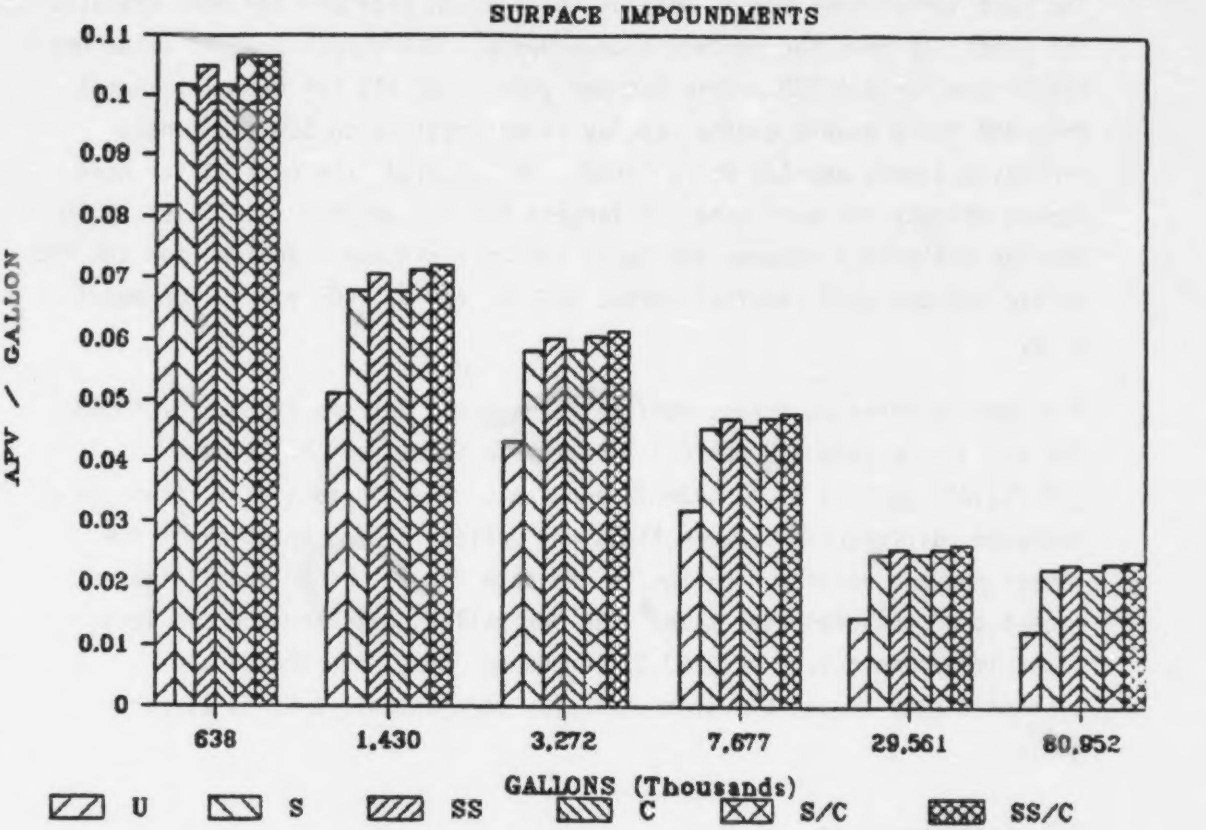

ANNUALIZED PRESENT VALUE PER MT
LANDFILLS
APV / MT
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0.5
2
5
7
15
35
60
123
MT / YEAR
U
S
SS
C
S/C
SS/C

FIGURE E-6

ANNUALIZED PRESENT VALUE PER GALLON



engineered facilities show costs of 2¢ per gallon for the 11 acres size and 10 or 11¢ per gallon for the quarter acre impoundment.

The cost differences across designs for a given size are far more dramatic for landfills than for surface impoundments. The annual present value per metric ton for a 5,000 metric ton per year landfill, for example, ranges from $98 for a double synthetic/clay lined facility to $80 for single synthetic lined, and $31 for unlined. As expected, the cost differences across designs for each size are largest for the smaller facilities; $198 per ton difference between the least and most stringent designs for the 500 metric ton per year landfill versus $29 for the 123,000 metric ton model size.

The cost differences across surface impoundment designs range from $0.03 for a .25 acre (638,307 gallon) facility to $0.01 for the 11 acre (80,951,673 gallon) model size impoundment. For the most part, these only represent differences between lined and unlined design costs since the annual present value per gallon is the same for all lined facilities, except the .25 acre model size. The per gallon costs for the smallest lined impoundment vary only $0.01 across designs, with the single synthetic/clay and double synthetic/clay more expensive at $0.11 per gallon.

2.3 Cost Functions

Our graphs of annualized cost per ton and per gallon showed that there are returns to scale in land disposal. They also seemed to show that cost and capacity exhibited a functional relation of the form:

$$\text{Cost} = a * \text{Capacity}^{b}$$

With cost functions of this form, b is a measure of returns to scale, since:

cost elasticity = percent change in cost/percent change in capacity = Marginal Cost / Average Cost, and

Marginal Cost = ba * Capacity^{b-1}, Average Cost = a * Capacity^{b}/Capacity, so:

$$\text{cost elasticity} = ba * \text{Capacity}^{b-1} * \text{Capacity}/\ a * \text{Capacity}^{b} = b$$

To fit this equation with a linear regression, it is necessary to perform a log-log transformation, since if $C = aQ^b$, then $\ln C = \ln a + b \ln Q$. Thus to estimate a and b, we regressed the log of the total and annual net present values for each design on the log of facility capacity (metric tons for landfills and gallons for surface impoundments). The cost functions for landfills are shown in Table E-44, and those for surface impoundments in Table E-45. (Due to the logarithmic transformation of both the dependent and independent variables, R^2s are not meaningful and are therefore not reported.)

Estimates of b, the cost elasticity (shown as exponents in the tables), are all less than 1, indicating increasing returns to scale. In the case of the single synthetic lined landfill (Table E-44), a 6.7% increase in the TPV would result from a 10% increase in facility size. For the unlined design, a 6.6% increase in the TPV would result from a 10% increase in facility size. Thus cost increases are less than linear with size increases.

2.4 Limits

This economic analysis used estimated engineering costs for the facility designs and sizes over an assumed period of time, rather than observed costs over actual facility lives. In the real world, we expect that although costs would be close to the engineering estimates, site specific factors would cause some variation, and that facility lives might well be different from the one we used here. Also, we assumed that facilities are able to use on-site clay in all designs requiring clay. If they are not able to do so, engineering costs would be larger, ranging from 12 to 53

TABLE E-44

LANDFILL COST FUNCTIONS

Liner Design	Total Cost Present Value	Annualized
Single Synthetic	$\$\ 24,045.78 * MT^{.67}$	$\$\ 1,624.75 * MT^{.67}$
Double Synthetic	$26,631.02 * MT^{.67}$	$1,788.39 * MT^{.67}$
Single Clay	$25,341.53 * MT^{.67}$	$1,706.18 * MT^{.67}$
Single Synthetic/Clay	$27,132.86 * MT^{.66}$	$1,826.59 * MT^{.66}$
Double Synthetic/Clay	$29,458.30 * MT^{.66}$	$2,110.51 * MT^{.66}$
Baseline - Unlined	$10,402.81 * MT^{.66}$	$696.40 * MT^{.66}$

MT = Metric Tons

TABLE E-45

SURFACE IMPOUNDMENT COST FUNCTIONS

Liner Design	Total Cost Present Value	Annualized
Single Synthetic	$ 94.81 * $G^{.69}$	$ 6.43 * $G^{.68}$
Double Synthetic	91.73 * $G^{.69}$	6.68 * $G^{.68}$
Single Clay	95.02 * $G^{.69}$	6.32 * $G^{.69}$
Single Synthetic/Clay	103.67 * $G^{.68}$	6.98 * $G^{.68}$
Double Synthetic/Clay	100.82 * $G^{.69}$	6.71 * $G^{.69}$
Baseline - Unlined	235.69 * $G^{.60}$	15.45 * $G^{.60}$

G = Gallons

percent more than those calculated, depending on facility design and size. Finally, we assume that all surface impoundments are on-site, and that smaller landfills are also on-site and do not require the fences, gates, office buildings, scales, and equipment the larger off-site facilities require.

In spite of these limitations in the analysis, given the inherent uncertainties in risk analysis, the costs are precise enough to provide a meaningful basis for cost/risk and cost/effectiveness analysis.

APPENDIX F

WASTE AND CONSTITUENT CHARACTERIZATION

1. INTRODUCTION

This document is one of eight appendices supporting the liner-location project report for EPA's Office of Solid Waste (OSW). This appendix describes and documents the waste characterization aspects of the project. The characterization of specific chemicals identified in the wastes is also documented here.

A primary objective of the waste characterization was to determine which hazardous waste streams were treated, stored, or disposed in the greatest quantities at the sample of TSD (treatment, storage, disposal) facilities visited by OSW in 1982 (hereafter referred to as site-visit facilities). These site-visit facilities have served as a source of background data for much of the liner-location analysis to date. The waste stream quantity information reported in the site-visit questionnaire was the starting point for the waste characterization of these facilities. The waste characterization included determination of the 10 highest quantity waste streams and the annual amount of each placed in land TSD facilities; selection of chemical constituents of concern for each waste stream and estimation of their concentrations; and estimation of the annual mass of each constituent placed in land TSD units at these facilities.

In addition to characterizing the hazardous waste streams at the site-visit facilities, the specific chemicals selected as waste stream constituents of concern were characterized. The physical, chemical, and toxicological parameters required by the liner-location risk model were determined for each constituent.

The liner-location risk model can be used to evaluate either the actual site-visit facilities or a set of hypothetical facilities. Analysis of site-visit facilities is based on the waste characterization as described in this appendix. A hypothetical facility analysis can be based on a few chemicals chosen from the chemical data base (and thus depends on the constituent characterization), but is not directly based on the waste characterization of site-visit facilities. However, constituent data derived from the waste characterization, such as amount disposed and frequency of occurrence, are useful for selecting chemicals for hypothetical facility analyses.

The remainder of this appendix is organized as follows:

- A brief description of the site-visit facility data base (Section 2);
- A description of the approach and specific methods used in the waste stream analysis and constituent characterization (Sections 3 and 4);
- The results of the waste stream analysis and constituent characterization (Sections 5 and 6); and
- The limitations of and possible uncertainties introduced by the waste stream and constituent characterization (Section 7).

2. SITE-VISIT FACILITY DATA BASE

Seventy site-visit facilities were included in the waste characterization. These 70 facilities comprise the "real" facilities used in the initial liner-location analyses. Table F-1 provides the identity and location of these site-visit facilities.

TABLE F-1

SITE VISIT FACILITIES

FACILITY NUMBER	FACILITY ID	LATITUDE			LONGITUDE		
		0	1	2	0	1	2
1	ALD000622464	32	48	8	88	18	33
2	ALD000770214	34	46	27	87	40	16
3	ALD004009007	33	14	42	87	29	40
4	CAD000060012	38	5	45	22	8	15
5	CAD000629998	36	42	43	19	47	13
6	CAD009108705	38	2	54	22	15	40
7	CAD009125923	37	31	5	22	0	41
8	CAD009205097	37	24	0	22	3	0
9	CAD009438300	37	30	55	22	15	30
10	CAD041844002	37	58	0	22	23	0
11	CAD990769465	36	16	39	19	38	56
12	CA7570024508	39	5	2	21	25	3
13	CTD001159300	41	52	44	71	52	55
14	CTD001160811	41	55	30	71	55	47
15	CTD001180462	41	11	59	73	7	28
16	CTD002344257	41	10	34	73	10	18
17	CTD003935905	41	32	30	72	33	32
18	CTD051320372	41	35	25	72	43	20
19	CTD056748205	41	17	30	72	55	30
20	FLD004073177	30	10	27	82	34	22
21	FLD043117522	27	10	45	80	13	52
22	FLD047966593	29	58	13	83	39	37
23	GAD000814541	33	33	45	85	4	20
24	GAD067560870	33	41	15	84	26	15
25	IAD000223354	41	35	8	91	2	30
26	IAD005173992	40	36	9	91	23	27
27	ILD041550567	41	39	0	88	3	30
28	ILD045063450	41	20	15	89	48	30
29	IND000780544	41	10	1	86	26	1
30	IND000810903	30	1	0	85	38	1
31	IND005159199	41	39	30	87	26	15
32	IND058689241	38	24	20	85	38	0
33	IND093220861	39	55	47	85	23	42
34	KYD055832091	38	11	54	85	52	20
35	LAD008058471	29	55	58	89	56	21
36	LAD008179707	29	56	0	89	58	18
37	LAD008184137	30	35	10	91	14	35
38	LAD008186579	30	1	12	91	24	0
39	MID000721753	42	10	16	83	10	0
40	MID000724831	42	13	15	83	31	14

TABLE F-1 (CONT)

SITE VISIT FACILITIES

FACILITY NUMBER	FACILITY ID	LATITUDE			LONGITUDE		
		0	1	2	0	1	2
41	MID005358130	43	22	44	84	37	30
42	NCD003154010	35	11	30	81	12	20
43	NJD002521961	40	26	58	74	20	14
44	NJD079320495	40	43	27	74	8	33
45	NM5890110518	34	58	30	6	32	2
46	OHD004222030	41	27	0	82	7	30
47	OHD068932011	39	15	29	84	27	41
48	OHD990747859	40	37	20	83	37	17
49	OKD000396549	34	37	47	97	10	15
50	OKD000803205	35	26	20	97	38	57
51	OKD057705972	34	12	20	97	5	40
52	OKD065438376	36	25	40	98	48	7
53	OKD980627046	35	14	10	97	27	50
54	OKD990695991	36	14	3	95	43	16
55	ORD089452353	45	37	30	20	22	30
56	PAD004344222	40	20	33	78	55	24
57	PAD004498010	40	18	15	79	52	35
58	SCD003345683	34	29	17	81	56	2
59	SCD036166372	34	36	0	82	7	0
60	SCD082228347	33	2	30	81	29	0
61	TXD000327429	29	43	50	95	4	35
62	TXD000782698	29	44	15	95	0	30
63	TXD007330202	32	26	17	94	41	24
64	TXD008117749	26	12	46	97	43	10
65	TXD026040709	28	51	25	96	0	11
66	TXD072181381	29	20	52	94	55	45
67	VAD065385206	37	18	15	77	16	21
68	WAD009276197	48	30	34	22	34	37
69	WVD005005509	38	23	25	81	46	43
70	WYD991501086	42	51	15	6	21	0

The site-visit facilities are a national sample of interim-status (as of 1982) land disposal facilities. OSW collected detailed information on these facilities through site visits and follow-up questionnaires. Among the relevant information collected are data on treatment, storage, and disposal (TSD) processes and technologies, facility costs and finances, and waste streams processed. OSW constructed the sample and collected the data to use in various analyses to support several regulatory initiatives, including the liner-location analysis. The site-visit facilities are not a random sample of all land disposal facilities; therefore, caution is necessary when extrapolating from the results of site-visit facility analyses to the universe of land disposal facilities.

Added to the limitations resulting from the non-randomness of the sample are limitations resulting from the voluntary participation in the sample and the self-reporting of the data. Especially relevant to the waste stream characterization is the self-reporting of waste stream identification and quantity information. The information was not independently verified. The inconsistent reporting format also increased the uncertainty of the extracted data (e.g., inconsistent quantity units, EPA waste stream ID numbers vs. written descriptions).

3. APPROACH -- WASTE STREAM ANALYSIS

Each site-visit facility was characterized in terms of the hazardous waste streams received in the base year, 1981. The following information was extracted or developed for each facility:

- Ten highest quantity hazardous waste streams for 1981 and the amounts received;
- Relevant technologies (landfill, surface impoundment, waste pile, land treatment) for each waste stream;

- Constituents of concern for each waste stream;

- Estimated waste stream concentrations for each constituent; and

- Annual amount of each constituent placed in each TSD technology.

This section describes the approach to deriving this information.

3.1 Data Extraction and Reduction

Waste stream data were extracted directly from the site-visit facility questionnaires made available by OSW. An initial attempt was made to derive the required data from computer summaries of the questionnaire data (provided by Development Planning and Research Associates, Inc.). However, it soon proved necessary to review the actual questionnaires both to confirm and supplement the summarized data.

For each site-visit facility, the reported identities and amounts of the 10 highest quantity waste streams were recorded. There were several inconsistencies in the data, including the following:

- Many sites reported fewer than 10 waste streams and it was not clear if that was all they received or if they chose not to report;

- Approximately 70 percent of waste streams were reported by their EPA ID number, with the remainder generally identified by a brief description; and

- Amounts received were reported in widely varying units of measurement, often in volume units without data on density. All amounts were converted to mass units, using any available density information. If unavailable, density was assumed to be 1.0 g/cc for liquids, 1.15 g/cc for sludges, and 1.6 g/cc for solids (based on 1 g/cc for water and 1.6 g/cc for soil).

In addition to waste stream identity and quantity data, the type of TSD technology was recorded for each waste stream. A few waste streams were placed serially into two separate technologies, and this was also noted.

Numerous waste streams were eliminated from the analysis at this point, primarily for one of two reasons. First, some reported waste streams were never placed in the land TSD technologies being evaluated (landfills, surface impoundments, waste piles and land treatment). These waste streams were usually either stored or treated in tanks or containers, incinerated, or injected underground. Any reported waste stream that was not placed in one of the above land TSD units was eliminated from the analysis (approximately 30 percent of all reported waste streams). Second, many reported waste streams were D001, D002, or D003 (unspecified ignitable, corrosive, or reactive waste). This analysis was designed to evaluate the long-term health risks of chronic exposures to toxicants. Hence, all D001, D002, and D003 wastestreams were eliminated (approximately 15 percent of all waste streams placed in a land TSD unit) as they are classified hazardous because of properties other than toxicity. 1/ The eliminated D001, D002, and D003 waste streams accounted for approximately 15 percent of the reported quantity of waste placed in a land TSD unit. Furthermore, the typical chemical composition of waste streams D001, D002, and D003 was unknown.

In total, approximately 45 percent of the waste streams were eliminated for these two reasons. A few additional waste streams were eliminated (approximately 5 percent) because of missing or insufficient data on waste stream quantity or composition. Two asbestos waste streams were eliminated from this analysis because of the particulate nature of asbestos and the low likelihood of groundwater transport.

1/ It is possible, however, that some of these waste streams may contain chronic toxicants as well as ignitables, corrosives, and reactives.

3.2 Determination of Constituents of Concern

It is impractical to quantitatively assess the risks of all the chemical constituents in many hazardous waste streams. Further, it is unnecessary to include all the waste stream constituents in a comparative risk assessment because one or two will usually produce much higher (orders of magnitude) risk projections than the other waste stream constituents. Thus, a few "constituents of concern" can be selected and used as indicators of the overall risk of the waste stream.

For each reported waste stream, constituents of concern were selected. Generally, two to five chemicals were chosen to represent multi-component waste streams. For single-component waste streams, a single constituent of concern was used. For the reported waste streams that are in the RCRA Risk-Cost Analysis Model 1/ data base (ICF Incorporated, 1984), constituents of concern already chosen for that model were used without modification. This accounted for approximately 90 percent of the site-visit facility waste streams.

The W-E-T waste stream constituents of concern were chosen on the basis of several factors contributing to overall health risk. However, only chemicals that are on the RCRA Appendix VIII list were considered. The primary selection criteria were relative concentration in the waste stream, toxicity (type of effect and potency), and overall environmental persistence. The constituents of concern were not chosen by a formal quantitative algorithm, but rather by expert judgment, taking the above-mentioned factors into account.

The 10 percent of the waste streams not in the W-E-T data base were treated similarly, with constituents of concern selected based on toxicity, relative concentration, and environmental persistence. For these waste

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1/ The RCRA Risk-Cost Analysis Model, developed for EPA's Office of Solid Waste, is commonly referred to as the Waste-Environment-Technology (W-E-T) model.

streams, composition information was obtained from two sources: (1) site-visit facility questionnaires for waste streams without EPA waste code numbers, and (2) EPA regulations (e.g., basis for listing) and background documents for waste streams with EPA waste code numbers.

Waste stream concentrations of the constituents of concern were estimated unless analytical data or estimates were given in the questionnaires. In cases where measurements were available (approximately 10 percent of the waste streams), the measured values were used. Otherwise, estimates were taken from the W-E-T data base when available. Concentrations for the remaining waste streams were estimated by various methods. Waste streams reported as D004 to D017 were assumed to contain the single designated constituent at 100 times the EP toxicity value (e.g., D007 was assumed to contain chromium at 500 mg/l). All P and U waste streams were assumed to contain a 90 percent mass fraction of the designated chemical (e.g., U002 was assumed to be acetone at 900,000 mg/kg). Constituent concentrations for the multi-chemical waste streams not in the W-E-T data base (approximately 10 percent of all waste streams) were estimated based on the description of the waste stream, the identity of the waste stream source, and knowledge of similar industrial hazardous waste streams.

After identification of the waste stream constituents of concern and estimation of their concentrations, the mass input for each constituent was calculated based on the reported waste stream quantities. This estimate represents the yearly mass input for 1981. The calculation was a straightforward multiplication of waste stream mass and constituent concentration, with appropriate unit conversions (e.g., facility LAD008179707 reported 141 tons of a waste stream containing lead, @ 2,000 ppm -- 141 tons x 0.002 x 908 kg/ton = 256 kg of lead). In the liner-location model, the constituent mass inputs are assumed to remain constant at the estimated 1981 rate for the 20 year facility life.

The next step was to convert the constituent mass inputs from waste stream-specific values to facility-specific values. This was accomplished by summing, for each land TSD technology type at a facility, the mass input of individual constituents that were present in more than one waste stream. For example, if three waste streams placed in the same landfill contained chromium, and the mass inputs were 400 kg/yr, 500 kg/yr, and 2,000 kg/yr, the total chromium input for that facility would be 2,900 kg/yr.

4. APPROACH -- CONSTITUENT CHARACTERIZATION

The liner-location model requires input of several chemical-specific parameters for risk estimation. The required parameters are water solubility, persistence, mobility in groundwater, and three toxicity parameters. The three physical/chemical parameters are used in the model to estimate chemical concentrations at exposure points, and the toxicity parameters are used to convert environmental concentrations to lifetime risks. The three toxicity parameters are H, the dose-response factor, which indicates the slope of the dose-response curve; K, a factor that indicates the shape of the dose-response curve (linear or quadratic); and S, a scaling factor to account for conservative assumptions in the derivation of H for threshold toxicants (non-carcinogens). These parameters and their derivation are discussed in detail in Appendix D, Risk Estimation Methodology. The approach to deriving the other three parameters is described in this section. In general, a conservative approach to estimating the parameters was taken. When data were unavailable or sparse, conservative values (i.e., values that would tend to overestimate risk) were selected.

4.1 Water Solubility

For organic constituents, water solubility values at 25°C were taken from standard secondary references (EPA, 1981; Dawson et al., 1980; Weast, 1979). Determination of a single value for inorganics was more problematic because of the large variation in solubility depending on the specific metal species present (e.g., water solubility of lead chloride = 9,900 mg/l; lead oxide = 17 mg/l; lead hydroxide = 140 mg/l; many species less than 0.1 mg/l). The solubility value used for inorganics was based on the solubility of the hydroxide species at 25°C and neutral pH.

4.2 Persistence

Values for constituent half-life in groundwater were based on values in the W-E-T model data base, which were derived from a literature survey of laboratory and field studies. 1/ Although oxidation and reduction, photolysis, hydrolysis, and biodegradation were considered in the derivation of these values, hydrolysis was the significant degradation mechanism for all constituents that were non-persistent in groundwater. If no information was located for a specific constituent, it was assumed to persist indefinitely in groundwater. The half-life values were converted to first order degradation rate constants using the following equation:

$$\lambda \text{ (rate constant)} = 0.69/\text{half-life (years)}$$

4.3 Mobility

Each chemical was placed in a mobility class based on its estimated retardation factor (Rd). Because of the necessity of limiting the groundwater modeling output, chemical-specific retardation factors were not used. The mobility class boundaries and median Rd values are given below:

Class	Rd Range	Median Rd
1	≤ 10	1.3
2	≥ 10 and ≤ 100	32
3	> 100 and $\leq 10{,}000$	360
4	$> 10{,}000$	160,000

1/ The values for the 10 non-persistent chemicals in the liner-location data base (Table F-5) were based on reports by Dilling et al. (1975), Al-Lohedan et al. (1982), Yaron and Saltzman (1978), and U.K. Department of the Environment (1976) and on professional judgment.

Because Class 4 chemicals were transported too slowly in all groundwater scenarios to appear at even the nearest well within the modeling time frame, these constituents were placed in Class 3 to allow a worst-case estimate of risks. The method for deriving retardation factors is summarized below.

The retardation factor is a measure of the rate at which the concentration profile for a reactive species is retarded relative to the transporting water mass. The majority of the constituents in the data base are organic chemicals, for which the principal retarding mechanism is adsorption on the surface of soil particles. Accordingly, the approach adopted here is based on a theoretical framework used to describe the partitioning of organic solutes between liquid and solid phases by adsorption. Other mechanisms are likely more important for inorganics, such as cation and anion exchange and precipitation (depending upon the pH and other factors). For simplicity, we have adopted a uniform approach that incorporates the behavior of inorganics into the framework developed for organics. The approach for organic chemicals is described first.

Adsorption of low or moderate concentrations of organic solutes in groundwater systems may be expressed by the Freundlich isotherm (Freeze and Cherry, 1979):

$$S = (Kd)\ C^{b}$$

S = mass of solute species adsorbed on the solids per unit bulk dry mass of the porous medium

C = solute concentration

Kd = distribution coefficient

b = an empirical constant

Kd and b depend on the solute species, the nature of the porous medium, and other conditions of the system. If adsorption is considered to be fast and reversible, b can be considered as unity, and adsorption can be described by Kd:

$$S = (Kd)\,C$$

In these cases, the retardation of a contaminant front relative to the bulk mass of water is described by:

$$\frac{V}{Vc} = 1 + \frac{\rho}{n}\,(Kd)$$

V = average linear velocity of the groundwater

Vc = velocity of the 0.5 point ($C/Co = 0.5$) on the concentration profile of the retarded constituent

ρ = bulk mass density of the porous medium

n = porosity of the porous medium

This expression is called the retardation factor, Rd, so that:

$$Rd = 1 + \frac{\rho}{n}\,(Kd)$$

For the purposes of the liner-location model, values of 0.2 and 2.0 g/cm^3 were selected for porosity and bulk density respectively. For unconsolidated granular deposits, porosity is commonly in the range of 0.2 to 0.4, although it can vary from 0 to 0.7 for certain types of earth materials. Bulk mass densities for unconsolidated granular deposits range from 1.6 to 2.1 g/cm^3 (Freeze and Cherry, 1979).

Using the selected values for porosity and bulk mass density, the retardation factor expression simplifies to:

$$Rd = 1 + 10 (Kd)$$

Values for Kd can be measured experimentally and are specific to the type and, in particular, to the organic carbon content of the soil. For Kd values that are orders of magnitude larger than 1, the solute is essentially immobile. The retardation factor for organics can be considered to be directly proportional to the fraction of organic carbon (Lyman et al., 1982), so that:

$$Rd = 1 + 10 (foc) (Koc)$$

foc = fraction of organic carbon

Koc = adsorption coefficient

In unpublished work by Walton and Davis (1983), values of foc in the range 0.001 to 0.1 were used for estimating Rd. Based on review of data on several soil types, from fine sand to silty clay loam, with a range of foc values from 0.005 to 0.04 (Davidson et al., 1980), a value of 0.02 was selected, so that the simplified expression for Rd is:

$$Rd = 1 + 0.2 (Koc)$$

An foc value of 0.02 is also considered reasonable as an average for clays, based on values for Mollisol and Entisol clays given by Davidson et al. (1980).

In the absence of experimental values, Koc can be estimated from the octanol-water partition coefficient, Kow. Various regression equations are reported by Lyman et al. (1982) for different classes of compounds, but the simplest approach and the one adopted here is a direct proportionality developed by Roberts (1981; cited in Walton and Davis, 1983) for a range of organic chemical classes, including aliphatic alcohols, alkanes and alkenes, aromatic hydrocarbons, halogenated aliphatics, halogenated aromatics, phenols and substituted phenols, carboxylic acids and nitrogenous compounds. The modified equation becomes:

$$\begin{aligned} Rd &= 1 + 0.2\ (0.63)\ (Kow) \\ &= 1 + 0.126\ (Kow) \end{aligned}$$

For inorganic chemicals, the retardation mechanisms are likely to be a more complex combination of sorption processes, which depend not only on soil type and conditions (pH, clay content, hydrous iron oxide content, ionic strength), but also on adsorbate concentration. Research in these areas (Fuller, 1978; Griffin and Shrimp, 1978) has found the experimental data to be better represented by the Langmuir isotherm equation:

$$S = \frac{K_1 b_1 C}{1+K_1 C}$$

S = amount of adsorbate adsorbed per gram of adsorbent

C = equilibrium concentration in solution

b_1 = the adsorption maximum

K_1 = constant (related to the bonding-energy of the adsorbate to the adsorbent)

Attempts to develop Freundlich Kd, and subsequently Rd, values from this type of information are complicated by the partial data available and the experimental conditions, which tend to reflect leachate from municipal landfills rather than segregated chemical landfills. Furthermore, calculated Rd values using these data are not consistent with the range of inorganic mobilities presented by Walton and Davis (1983), which were considered to be the most comprehensive and reliable review of relative mobilities available.

Walton and Davis (1983) estimated Rd values for heavy metals in the range of 10^3 to 10^5 and for arsenic and hexavalent chromium in the range of 1 to 10. These values were used to assign the inorganics to mobility classes. Data from Fuller (1978) and Griffin and Shrimp (1978) were used to provide further detail on the relative mobilities of individual inorganic constituents.

5. RESULTS -- WASTE STREAM ANALYSIS

There were 62 site-visit facilities that reported placement of toxic wastes in at least one of the four land TSD technologies being evaluated. These facilities were analyzed as described in Section 3. The other eight facilities either reported no on-site land treatment, storage, or disposal or reported only D001, D002, or D003 wastes (one site was eliminated due to insufficient information).

Table F-2 gives the relevant reported waste streams for the 62 site-visit facilities. Waste streams reported by a description rather than an EPA waste code number are usually designated by a code of X followed by three numbers. For each waste stream, the selected constituents of concern are listed along with their estimated waste stream concentrations. There are a few apparent inconsistencies in the exhibit as a result of the use of reported analytical data when available. For example, two waste streams with the same waste code number may have different constituents or concentrations listed. This reflects the use of specific data in one case and generic information in another.

The mean number of waste streams reported per site is 5.0, with a range of 1 to 10. The mean number of relevant waste streams reported for the 62 facilities comprising our sample is 2.4, reflecting the exclusion of waste streams as described in Section 3.

TABLE F-2

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
ALD000622464	D007	CHROMIUM	500.000
	D008	LEAD	500.000
	F001	TRICHLOROETHYLENE	50000.000
		1,1,1-TRICHLOROETHANE	50000.000
		METHYLENE CHLORIDE	50000.000
	F003	ETHYL BENZENE	10000.000
		M. ISOBUTYL KETONE	10000.000
	F005	CARBON DISULFIDE	10000.000
	F006	CHROMIUM	37.000
		CYANIDES	4.300
	K061	CHROMIUM	450.000
		LEAD	140.000
CAD000060012	D001	CADMIUM	15.000
		CHROMIUM	10.000
	D007	CHROMIUM	500.000
	K049	CHROMIUM	0.800
		LEAD	29.000
	X131	TRICHLOROETHYLENE	50000.000
		1,1,1-TRICHLOROETHANE	50000.000
		METHYLENE CHLORIDE	50000.000
		CARBON DISULFIDE	10000.000
	X132	CHROMIUM	500.000
		LEAD	500.000
	X133	CHROMIUM	500.000
CAD000629998	X138	DINOSEB	100.000
		DIMETHOATE	100.000
		ENDOSULFAN	100.000
		PARATHION	100.000
		PENTACHLOROPHENOL	100.000
		PCNITROBENZENE	100.000
	X139	DINOSEB	100.000
		DIMETHOATE	100.000
		ENDOSULFAN	100.000
		PARATHION	100.000
		PCPHENOL	100.000
		PCNITROBENZENE	100.000
CAD009108705	K048	CHROMIUM	275.000
		LEAD	27.000
	K051	CHROMIUM	400.000
		LEAD	77.000
	X132	CHROMIUM	110.000
		LEAD	60.000
	X132	CHROMIUM	125.000
		LEAD	52.000
CAD009125923	X000	CHROMIUM	500.000
		LEAD	500.000

TABLE F-2 (CONT)

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
CAD009438300	F006	CHROMIUM	37.000
		CYANIDES	4.300
CAD041844002	F006	CHROMIUM	37.000
		CYANIDES	4.300
	K051	CHROMIUM	17.000
		LEAD	310.000
	K052	ARSENIC	29.400
		LEAD	79.000
	X215	CADMIUM	100.000
		MERCURY	20.000
CAD990769465	K061	CHROMIUM	450.000
		LEAD	140.000
CA7570024508	X227	CADMIUM	100.000
	X237	CHROMIUM	500.000
CTD001160811	F006	CHROMIUM	37.000
		CYANIDES	4.300
	F009	NICKEL	170.000
CTD001180462	F006	CHROMIUM	37.000
		CYANIDES	4.300
CTD002344257	K061	CHROMIUM	450.000
		LEAD	140.000
	K062	CHROMIUM	86.700
		LEAD	9.800
	X133	CHROMIUM	500.000
	X127	CHROMIUM	86.700
		LEAD	9.800
CTD003935905	X208	CHROMIUM	500.000
	X209	CHROMIUM	37.000
		CYANIDES	4.300
CTD051320372	F001	TRICHLOROETHYLENE	50000.000
		1,1,1-TRICHLOROETHANE	50000.000
		METHYLENE CHLORIDE	50000.000
CTD056748205	F009	CYANIDES	60000.000
FLD004073177	D007	CHROMIUM	65.000
FLD043117522	F019	CHROMIUM	37.000
		CYANIDES	4.300
FLD047966593	F006	CHROMIUM	3.000
GAD000814541	D008	LEAD	500.000
	X106	LEAD	500.000
		CADMIUM	100.000
GAD067560870	K001	BENZ(A)PYRENE	0.200
		CHRYSENE	0.500
		PENTACHLOROPHENOL	3.000
IAD000223354	K061	CHROMIUM	450.000
		LEAD	140.000

TABLE F-2 (CONT)

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
IAD005173992	U188	PHENOL	1260.000
ILD041550567	K051	CHROMIUM	282.000
		LEAD	20.000
ILD045063450	D007	CHROMIUM	500.000
	D009	MERCURY	20.000
	F002	TETRACHLOROETHYLENE	60000.000
	F003	ETHYL BENZENE	10000.000
		M. ISOBUTYL KETONE	10000.000
	F004	TOLUENE	40000.000
	F006	CHROMIUM	37.000
		CYANIDES	4.300
	U190	PHTHALIC ANHYDRIDE	900000.000
IND000780544	F006	CHROMIUM	37.000
		CYANIDES	4.300
	D008	LEAD	500.000
	F002	TETRACHLOROETHYLENE	60000.000
	F003	ETHYL BENZENE	10000.000
		M. ISOBUTYL KETONE	10000.000
IND000810903	K062	LEAD	13.500
IND005159199	K061	CHROMIUM	450.000
		LEAD	140.000
	X106	LEAD	500.000
		CADMIUM	100.000
IND093220861	K062	CHROMIUM	86.700
		LEAD	9.800
KYD055832091	U122	FORMALDEHYDE	10000.000
	U220	TOLUENE	800.000
LAD008058471	K048	CHROMIUM	3.000
		LEAD	27.000
	K049	CHROMIUM	0.800
		LEAD	29.000
	K050	CHROMIUM	0.600
		LEAD	7.800
	K051	CHROMIUM	17.000
		LEAD	310.000
LAD008179707	K051	CHROMIUM	17.000
		LEAD	310.000
	K052	ARSENIC	29.400
		LEAD	79.000
	X102	LEAD	4000.000
		BENZ(A)ANTHRACENE	1000.000
		BENZ(A)PYRENE	1000.000
	X103	CYANIDES	7.400
		LEAD	2.500
	X235	LEAD	2000.000
		BENZ(A)ANTHRACENE	4000.000
		BENZ(A)PYRENE	1000.000

TABLE F-2 (CONT)

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
LAD008184137	D008	LEAD	500.000
LAD008186579	D007	CHROMIUM	500.000
	D008	LEAD	500.000
	K050	CHROMIUM	0.600
		LEAD	7.800
	K051	CHROMIUM	17.000
		LEAD	310.000
MID000721753	K062	CHROMIUM	86.700
		LEAD	9.800
MID000724831	X619	CHROMIUM	500.000
		CYANIDES	4.300
		LEAD	500.000
	K061	CHROMIUM	450.000
		LEAD	140.000
MID005358130	K051	CHROMIUM	3.400
		LEAD	0.500
	K052	ARSENIC	0.0
		LEAD	16.500
NCD003154010	F006	CHROMIUM	37.000
		CYANIDES	4.300
NJD079320495	K100	LEAD	500.000
		CADMIUM	100.000
NM5890110518	D008	LEAD	500.000
	F001	TRICHLOROETHYLENE	50000.000
		1,1,1-TRICHLOROETHANE	50000.000
		METHYLENE CHLORIDE	50000.000
	F003	ETHYL BENZENE	10000.000
		M. ISOBUTYL KETONE	10000.000
	U002	ACETONE	900000.000
	U220	TOLUENE	900000.000
OHD004222030	D007	CHROMIUM	500.000
	K087	NAPHTHALENE	78000.000
		PHENOL	3.000
	X202	LEAD	500.000
OHD068932011	K086	CHROMIUM	15.000
		LEAD	76.000
	X136	CHROMIUM	670.000
		LEAD	330.000
		CYANIDES	330.000
OHD990747859	U188	PHENOL	5500.000
OKD000396549	K049	CHROMIUM	0.900
		LEAD	170.000
OKD057705972	K051	CHROMIUM	17.000
		LEAD	310.000

TABLE F-2 (CONT)

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
OKD065438376	F006	CHROMIUM	37.000
		CYANIDES	4.300
	X215	CADMIUM	100.000
		MERCURY	20.000
		ARSENIC	500.000
		CHROMIUM	500.000
OKD980627046	K051	CHROMIUM	17.000
		LEAD	310.000
OKD990695991	X222	ACETONE	100.000
ORD089452353	D008	LEAD	500.000
	D009	MERCURY	20.000
	D016	LINDANE	40.000
	F006	CHROMIUM	37.000
		CYANIDES	4.300
	U188	PHENOL	900000.000
PAD004344222	D006	CADMIUM	100.000
	D008	LEAD	500.000
	K061	CHROMIUM	450.000
		LEAD	140.000
	K062	CHROMIUM	86.700
		LEAD	9.800
	K087	NAPHTHALENE	66.000
		PHENOL	3.000
PAD004498010	K024	PHTHALIC ANHYDRIDE	36000.000
		TRICHLOROETHYLENE	36000.000
SCD003345683	X219	TRICHLOROETHYLENE	25000.000
		1,1,1-TRICHLOROETHANE	25000.000
		METHYLENE CHLORIDE	25000.000
		TETRACHLOROETHYLENE	30000.000
SCD036166372	U080	METHYLENE CHLORIDE	120000.000
SCD082228347	U002	ACETONE	900000.000
	U169	NITROBENZENE	900000.000
TXD000327429	X112	TETRACHLOROETHYLENE	500000.000
		CARBON TETRACHLORID	500000.000
		MERCURY	20.000
		CYANIDES	60000.000
TXD000782698	X121	CADMIUM	2.500
		CHROMIUM	0.300
TXD007330202	F005	CARBON DISULFIDE	10000.000
	X113	CHLOROFORM	150.000
		FORMALDEHYDE	150.000
		ACETALDEHYDE	8100.000
		CHLOROACETALDEHYDE	5950.000
TXD008117749	X618	ARSENIC	100.000
		PARATHION	100.000
		METHOMYL	100.000
		TOXAPHENE	100.000

TABLE F-2 (CONT)

WASTE STREAMS AND CONSTITUENTS OF CONCERN AT SITE VISIT FACILITIES

FACILITY ID	EPA NUMBER	CONSTITUENTS	CONCENTRATION (PPM)
TXD026040709	X114	CARBON DISULFIDE	10000.000
		ETHYL BENZENE	10000.000
		CHLOROACETALDEHYDE	11900.000
		1,1,1-TRICHLOROETHANE	50000.000
		METHYLENE CHLORIDE	50000.000
		M. ISOBUTYL KETONE	10000.000
		TRICHLOROETHYLENE	50000.000
	X115	TRICHLOROETHYLENE	50000.000
		1,1,1-TRICHLOROETHANE	50000.000
		CHLOROACETALDEHYDE	11900.000
		METHYLENE CHLORIDE	50000.000
		CARBON DISULFIDE	10000.000
	X116	CARBON DISULFIDE	10000.000
TXD072181381	K051	CHROMIUM	700.000
		LEAD	37.000
	X108	CHROMIUM	700.000
		LEAD	37.000
	X111	CHROMIUM	500.000
WAD009276197	K049	CHROMIUM	1500.000
		LEAD	110.000
	K051	CHROMIUM	1900.000
		LEAD	250.000
	K052	ARSENIC	29.400
		LEAD	480.000
	X615	CHROMIUM	230.000
		LEAD	20.000
WVD005005509	P064	M. ISOCYANATE	900000.000
	U223	TDI	900000.000
	WH20	ACRYLONITRILE	1000.000
		BENZENE	500.000
		1,2-DICHLOROBENZENE	10.000
WYD991501086	K051	CHROMIUM	550.000
		LEAD	202.000

The information in Table F-2 was used to develop a list of unique constituents of concern for each technology type at the 62 site-visit facilities. This was done by summing all mass inputs of the same constituent in different waste streams going into the same TSD unit. These results are shown in Table F-3, which gives the unique constituents of concern for each facility and the total annual mass input of each. The distribution of relevant land TSD technologies at the 62 facilities is as follows: 37 had surface impoundments, 17 had landfills, 17 had land treatment and 10 had waste piles (only technologies receiving toxic hazardous wastes are included in these numbers).

Forty-five different constituents of concern were selected from the reported waste streams at the site-visit facilities. Most of them are solvents, metals, industrial chemical intermediates, or pesticides commonly found in hazardous wastes. Table F-4 lists the ten most frequently occurring constituents of concern at the site-visit facilities. Metals and solvents were by far the most frequent constituents of concern in the reported waste streams.

6. RESULTS -- CONSTITUENT CHARACTERIZATION

The 45 chemicals selected as constituents of concern were characterized as described in Section 3. The results of this characterization are given in Table F-5, which lists the constituents and the values used for solubility, persistence, mobility, and toxicity.

7. LIMITATIONS OF THE WASTE AND CONSTITUENT CHARACTERIZATION

A number of assumptions and simplifications were made in the waste and constituent characterization that introduce uncertainty to the risk analysis. These assumptions were pointed out in the previous sections and are summarized here. Generally, the limitations result from either:

TABLE F-3

TOTAL CONSTITUENT MASS INPUTS BY DISPOSAL TYPE AT SITE VISIT FACILITIES

FACILITY ID	DISPOSAL TYPE	CONSTITUENT	MASS INPUT(KG/YR)
ALD000622464	LF	CHROMIUM	4900.000
		LEAD	2600.000
		TRICHLOROETHYLENE	130000.000
		1,1,1-TRICHLOROETHAN	130000.000
		METHYLENE CHLORIDE	130000.000
		ETHYL BENZENE	41000.000
		METHYL ISOBUTYL KETONE	41000.000
		CARBON DISULFIDE	28000.000
		CYANIDES	41.000
CAD000060012	LF	CHROMIUM	11000.000
		LEAD	3100.000
		TRICHLOROETHYLENE	730000.000
		1,1,1-TRICHLOROETHAN	730000.000
		METHYLENE CHLORIDE	730000.000
		CARBON DISULFIDE	150000.000
	SI	CHROMIUM	5200.000
		LEAD	3100.000
	LT	CADMIUM	88.000
		CHROMIUM	59.000
CAD000629998	LF	DINOSEB	500.000
		DIMETHOATE	500.000
		ENDOSULFAN	500.000
		PARATHION	500.000
		PENTACHLOROPHENOL	500.000
		PCNITROBENZENE	500.000
	SI	DINOSEB	360.000
		DIMETHOATE	360.000
		ENDOSULFAN	360.000
		PARATHION	360.000
		PENTACHLOROPHENOL	360.000
		PCNITROBENZENE	360.000
CAD009108705	LT	CHROMIUM	940.000
		LEAD	390.000
CAD009125923	SI	CHROMIUM	85.000
		LEAD	85.000
CAD009438300	SI	CHROMIUM	3.200
		CYANIDES	0.370
CAD041844002	SI	CHROMIUM	500.000
		LEAD	580.000
		ARSENIC	500.000
		CADMIUM	100.000
		MERCURY	20.000
CAD990769465	WP	CHROMIUM	1300.000
		LEAD	410.000

TABLE F-3 (CONT)

TOTAL CONSTITUENT MASS INPUTS BY DISPOSAL TYPE AT SITE VISIT FACILITIES

FACILITY ID	DISPOSAL TYPE	CONSTITUENT	MASS INPUT(KG/YR)
CA7570024508	SI	CADMIUM	13.000
		CHROMIUM	14000.000
CTD001160811	SI	CHROMIUM	0.050
		CYANIDES	0.005
		NICKEL	1.500
CTD001180462	WP	CHROMIUM	5.100
		CYANIDES	0.590
	SI	CHROMIUM	5.100
		CYANIDES	0.590
CTD002344257	WP	CHROMIUM	220.000
		LEAD	68.000
	SI	CHROMIUM	460.000
	LF	CHROMIUM	5.500
		LEAD	0.620
CTD003935905	LF	CHROMIUM	3400.000
		CYANIDES	2.800
	SI	CHROMIUM	24.000
		CYANIDES	2.800
CTD051320372	SI	TRICHLOROETHYLENE	2100.000
		1,1,1-TRICHLOROETHANE	2100.000
		METHYLENE CHLORIDE	2100.000
CTD056748205	SI	CYANIDES	2500.000
FLD004073177	SI	CHROMIUM	0.047
	LT	CHROMIUM	0.047
FLD043117522	SI	CHROMIUM	5.600
		CYANIDES	0.650
FLD047966593	LT	CHROMIUM	0.009
GAD000814541	WP	LEAD	241.000
		CADMIUM	47.000
GAD067560870	SI	BENZ(A)PYRENE	0.025
		CHRYSENE	0.060
		PCPHENOL	0.340
IAD000223354	WP	CHROMIUM	980.000
		LEAD	310.000
IAD005173992	SI	PHENOL	19.100
ILD041550567	SI	CHROMIUM	500.000
		LEAD	35.000
	LT	CHROMIUM	500.000
		LEAD	35.000
ILD045063450	LF	CHROMIUM	410.000
		MERCURY	31.000
		TETRACHLOROETHYLENE	33000.000
		ETHYL BENZENE	9300.000
		METHYL ISOBUTYL KETONE	9300.000
		TOLUENE	23000.000
		PHTHALIC ANHYDRIDE	320000.000

TABLE F-3 (CONT)

TOTAL CONSTITUENT MASS INPUTS BY DISPOSAL TYPE AT SITE VISIT FACILITIES

FACILITY ID	DISPOSAL TYPE	CONSTITUENT	MASS INPUT(KG/YR)
IND000780544	LF	CHROMIUM	260.000
		CYANIDES	29.000
		LEAD	330.000
		TETRACHLOROETHYLENE	33000.000
		ETHYL BENZENE	5600.000
		METHYL ISOBUTYL KETONE	5600.000
IND000810903	SI	LEAD	3.000
	LT	LEAD	3.000
IND005159199	WP	CHROMIUM	2800.000
		LEAD	1200.000
		CADMIUM	58.000
IND093220861	SI	CHROMIUM	120.000
		LEAD	13.000
KYD055832091	SI	FORMALDEHYDE	5800.000
		TOLUENE	11000.000
LAD008058471	SI	CHROMIUM	38.000
		LEAD	660.000
	LT	CHROMIUM	38.000
		LEAD	660.000
LAD008179707	SI	CHROMIUM	450.000
		LEAD	8100.000
	LF	ARSENIC	41.000
		LEAD	420.000
		BENZ(A)ANTHRACENE	530.000
		BENZ(A)PYRENE	140.000
LAD008184137	WP	LEAD	5400.000
LAD008186579	SI	CHROMIUM	3100000.00
		LEAD	6.000
	LT	LEAD	4.100
	LF	CHROMIUM	7.300
		LEAD	130.000
MID000721753	SI	CHROMIUM	950.000
		LEAD	110.000
MID000724831	WP	CHROMIUM	140000.000
		CYANIDES	19.000
		LEAD	45000.000
MID005358130	LT	CHROMIUM	2.300
		LEAD	0.450
NCD003154010	SI	CHROMIUM	4.900
		CYANIDES	0.570
NJD079320495	SI	LEAD	11000.000
		CADMIUM	2200.000
NM5890110518	LF	TRICHLOROETHYLENE	11.000
		1,1,1-TRICHLOROETHANE	11.000
		METHYLENE CHLORIDE	11.000
		ETHYL BENZENE	20.000
		METHYL ISOBUTYL KETONE	20.000
		ACETONE	2100.000
		TOLUENE	140.000

TABLE F-3 (CONT)

TOTAL CONSTITUENT MASS INPUTS BY DISPOSAL TYPE AT SITE VISIT FACILITIES

FACILITY ID	DISPOSAL TYPE	CONSTITUENT	MASS INPUT(KG/YR)
OHD004222030	WP	CHROMIUM	2.400
	LF	NAPHTHALENE	120000.000
		PHENOL	4.500
		LEAD	29.000
OHD068932011	LF	CHROMIUM	660.000
		LEAD	330.000
		CYANIDES	320.000
	SI	CHROMIUM	660.000
		LEAD	320.000
		CYANIDES	320.000
OHD990747859	SI	PHENOL	570.000
OKD000396549	LT	CHROMIUM	13.000
		LEAD	250.000
OKD057705972	LT	CHROMIUM	20.000
		LEAD	370.000
OKD065438376	LF	CHROMIUM	8800.000
		CYANIDES	26.000
		CADMIUM	1700.000
		MERCURY	340.000
		ARSENIC	8600.000
OKD980627046	LT	CHROMIUM	0.390
		LEAD	7.000
OKD990695991	SI	ACETONE	140.000
ORD089452353	LF	LEAD	2800.000
		MERCURY	230.000
		LINDANE	43.000
		CHROMIUM	150.000
		CYANIDES	17.000
		PHENOL	620000.000
PAD004344222	WP	CADMIUM	53.000
		LEAD	5700.000
		CHROMIUM	1200.000
		NAPHTHALENE	13.000
PAD004498010	SI	PHTHALIC ANHYDRIDE	25000.000
		TRICHLOROETHYLENE	25000.000
SCD003345683	SI	TRICHLOROETHYLENE	3500.000
		1,1,1-TRICHLOROETHANE	3500.000
		METHYLENE CHLORIDE	3500.000
		TETRACHLOROETHYLENE	4200.000
SCD036166372	SI	METHYLENE CHLORIDE	2100.000
SCD082228347	SI	ACETONE	2800.000
		NITROBENZENE	680.000
	LT	ACETONE	2800.000
		NITROBENZENE	680.000

TABLE F-3 (CONT)

TOTAL CONSTITUENT MASS INPUTS BY DISPOSAL TYPE AT SITE VISIT FACILITIES

FACILITY ID	DISPOSAL TYPE	CONSTITUENT	MASS INPUT(KG/YR)
TXD000327429	LF	TETRACHLOROETHYLENE	27.000
		CARBON TETRACHLORID	18.000
		CYANIDES	1.200
TXD000782698	LT	CADMIUM	53.000
		CHROMIUM	6.400
TXD007330202	SI	CARBON DISULFIDE	150.000
		CHLOROFORM	490000.000
		FORMALDEHYDE	490000.000
		ACETALDEHYDE	26000000.0
		CHLOROACETALDEHYDE	20000000.0
TXD008117749	SI	ARSENIC	33.000
		PARATHION	33.000
		METHOMYL	33.000
		TOXAPHENE	33.000
TXD026040709	SI	CARBON DISULFIDE	12000000.0
		ETHYL BENZENE	8700000.00
		CHLOROACETALDEHYDE	14000000.0
		1,1,1-TRICHLOROETHANE	61000000.0
		METHYLENE CHLORIDE	61000000.0
		METHYL ISOBUTYL KETONE	8700000.00
		TRICHLOROETHYLENE	61000000.0
	LF	TRICHLOROETHYLENE	22000.000
		1,1,1-TRICHLOROETHANE	22000.000
		ETHYL BENZENE	4400.000
		METHYL ISOBUTYL KETONE	4400.000
		CHLOROACETALDEHYDE	5200.000
TXD072181381	LT	CHROMIUM	4100.000
		LEAD	220.000
WAD009276197	LT	CHROMIUM	560.000
		LEAD	49.000
WVD005005509	LF	METHYL ISOCYANATE	67000.000
		TDI	5600.000
	SI	ACRYLONITRILE	6400000.00
		BENZENE	3200000.00
		1,2-DICHLOROBENZENE	64000.000
WYD991501086	LT	CHROMIUM	660.000
		LEAD	240.000

TABLE F-4

TEN CONSTITUENTS OF CONCERN OCCURRING MOST FREQUENTLY AT SITE-VISIT FACILITIES

Rank	Chemical	Percent of Facilities
1	Chromium	66%
2	Lead	52%
3	Cyanide	27%
4	Cadmium	14%
5	Trichloroethylene	13%
6	Arsenic	10%
6	1,1,1-Trichloroethane	10%
6	Dichloromethane	10%
6	Ethyl Benzene	10%
10	Phenol	8%
10	Methyl Isobutyl Ketone	8%

TABLE F-5

CONSTITUENTS OF CONCERN AT SITE-VISIT FACILITIES

CONSTITUENT	WATER SOLUBILITY(PPM)	GROUNDWATER HALF-LIFE(YRS)	MOBILITY CLASS	UNIT RISK (H)	SCALING INDEX (S)	DOSE RESPONSE (K)	TYPE OF EFFECT
ACENAPHTHENE	0.3420E+01	PERSISTENT	3	0.1150E+02	1.0	1	CANCER
ACETALDEHYDE	0.1000E+07	PERSISTENT	1	0.1590E-03	0.5	2	TRACHEA
ACETONE	0.1000E+07	PERSISTENT	1	0.8000E-05	0.5	2	STOMACH
ACRYLONITRILE	0.7900E+05	PERSISTENT	1	0.2400E+00	1.0	1	CANCER
ARSENIC	0.5000E+02	PERSISTENT	2	0.1400E+02	1.0	1	CANCER
BENZENE	0.1800E+04	PERSISTENT	2	0.5200E-01	1.0	1	CANCER
BENZ(A)ANTHRACENE	0.5700E-02	PERSISTENT	4	0.1150E+02	1.0	1	CANCER
BENZ(A)PYRENE	0.3800E-02	PERSISTENT	4	0.1150E+02	1.0	1	CANCER
CADMIUM	0.1000E+03	PERSISTENT	2	0.6650E+01	1.0	1	CANCER
CARBON DISULFIDE	0.2000E+00	PERSISTENT	1	0.5300E-01	1.0	2	EMBRYOGENESIS
CARBON TETRACHLORID	0.7850E+03	PERSISTENT	2	0.1300E+00	1.0	1	CANCER
CHLOROACETALDEHYDE	0.4000E+06	PERSISTENT	1	0.3760E+02	0.5	2	BLOOD AND LUNGS
CHLOROFORM	0.8200E+04	1.23	1	0.1100E+00	1.0	1	CANCER
CHROMIUM (VI)	0.4000E+05	PERSISTENT	2	0.2000E-01	0.5	2	KIDNEY AND LIVER
CHRYSENE	0.1800E-02	PERSISTENT	4	0.1150E+02	1.0	1	CANCER
CYANIDES	0.4800E+06	4.00	1	0.1000E+00	0.5	2	THYROID
DIMETHOATE	0.4800E+02	PERSISTENT	2	0.5310E+01	0.1	2	BLOOD ENZYME
1,2-DICHLOROBENZENE	0.1000E+03	PERSISTENT	3	0.3400E-03	0.5	2	KIDNEY AND LIVER
DINOSEB	0.1120E+02	PERSISTENT	3	0.3200E-03	1.0	2	EMBRYOGENESIS
ENDOSULFAN	0.5000E+00	PERSISTENT	1	0.3000E-02	0.5	2	KIDNEY
ETHYL BENZENE	0.2060E+03	PERSISTENT	3	0.5760E-03	0.5	2	KIDNEY AND LIVER
FORMALDEHYDE	0.3000E+06	PERSISTENT	1	0.7700E+00	0.5	2	WEIGHT
HEXACHLOROCYCLOPENT	0.3200E+01	PERSISTENT	3	0.1000E+07	0.1	2	BLOOD
LEAD	0.1400E+03	PERSISTENT	2	0.1250E+10	0.1	4	BLOOD
LINDANE	0.1000E-02	PERSISTENT	3	0.1330E+01	1.0	1	CANCER
MERCURY	0.5000E+02	PERSISTENT	3	0.6900E+00	0.5	2	KIDNEY
METHOMYL	0.6300E+03	PERSISTENT	1	0.6940E-02	0.5	2	BLOOD AND SPLEEN
METHYLENE CHLORIDE	0.2000E+05	1.48	1	0.4500E-02	1.0	1	CANCER
M. ISOBUTYL KETONE	0.1500E+01	PERSISTENT	1	0.4480E-03	0.5	2	KIDNEY
M. ISOCYANATE	0.6700E+01	0.000005	3	0.7900E+01	0.5	2	LUNGS
MOLYBDENUM	0.5000E+02	PERSISTENT	2	0.1480E+03	0.5	2	KIDNEY AND LIVER
NAPHTHALENE	0.3440E+02	PERSISTENT	2	0.1000E-03	0.5	2	EYE
NICKEL	0.5000E+02	PERSISTENT	2	0.9000E+01	1.0	2	REPRODUCTIVE SYST
NITROBENZENE	0.1900E+04	PERSISTENT	1	0.1800E-01	0.5	2	MULTIPLE ORGANS
PARATHION	0.2000E+02	0.33	3	0.6940E+06	0.1	2	BLOOD ENZYME
PENTACHLOROPHENOL	0.1400E+02	PERSISTENT	3	0.1600E-01	1.0	2	EMBRYOGENESIS
PCNITROBENZENE	0.4000E+00	PERSISTENT	3	0.7000E+00	1.0	1	CANCER
PHENOL	0.9300E+05	PERSISTENT	1	0.1000E-01	0.5	2	KIDNEY
PHTHALIC ANHYDRIDE	0.6170E+04	0.00007	1	0.4000E-06	0.5	2	WEIGHT
TETRACHLOROETHYLENE	0.2000E+03	0.72	2	0.5310E-01	1.0	1	CANCER
TOLUENE	0.5350E+03	PERSISTENT	2	0.9400E-03	0.1	2	WEIGHT
TDI	0.5000E+03	0.000005	3	0.4300E-02	1.0	1	CANCER
TOXAPHENE	0.5000E+00	PERSISTENT	3	0.1130E+01	1.0	1	CANCER
TRICHLOROETHYLENE	0.1100E+04	0.88	2	0.1300E-01	1.0	1	CANCER
1,1,1-TRICHLOROETHAN	0.7200E+03	0.50	2	0.9900E-03	1.0	1	CANCER

- Assumptions made in the absence of data (e.g., waste stream density or constituent concentration estimates); or

- Simplifications made to limit the scope of the model (e.g., use single constituent parameter values for inorganics).

Table F-6 lists the major assumptions made.

Each assumption increases the uncertainty of the model results. Some assumptions related to wastestream composition affect only analyses of the site-visit facilities, whereas the assumptions made in deriving constituent parameters affect all analyses using the model. Interpretation of the liner-location risk analysis results must take into account these assumptions and the associated uncertainty.

TABLE F-6

MAJOR SOURCES OF UNCERTAINTY INTRODUCED BY THE WASTE CHARACTERIZATION

	Effect on Risk Estimates			Applicability	
Assumption/Source of Uncertainty	Increases	Decreases	Either	Site-Visit Analyses	All Analyses
Using self-reported waste stream data			X	X	
Using 1981 waste stream data to estimate inputs over facility lite/assuming 20-year facility life			X	X	
Limitation to 10 highest quantity waste streams per site		X		X	
Eliminating waste streams D001, D002, and D003		X		X	
Waste stream density assumptions			X	X	
Waste stream composition assumptions			X	X	
Choosing and modeling only a few constituents of concern for each waste stream		X			X
Constituent concentration assumptions			X	X	
Using single values for constituent parameters (especially inorganics)			X		X
Using class values for constituent mobility			X		X
Conservative approach to determining constituent parameters	X				X

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APPENDIX G

STRUCTURE AND FUNCTION OF THE MODEL

1. INTRODUCTION

This document is one of eight appendices developed as part of the liner-location project report. The purpose of this appendix is to document the structure and function of the model, and to describe how ICF integrated the various components into a complete risk analysis model. This is especially important because the individual model components were developed by several different firms; thus, the approach to integrating these components must be explicitly documented. The objective here is not to describe the individual components in detail, as each major component of the model is covered in a separate appendix. Rather, the intention is to explain the interactions of the various components within the overall model framework. This appendix focuses on model logic, information flow, and the linkages between components. Details of the major individual model components are provided in the following appendices:

- Appendix A - failure/release model;
- Appendix B - subsurface transport model; and
- Appendix D - risk estimation model.

In addition, the documentation of model input data is described in Appendix F (Waste and Constituent Characterization) and C (Exposure Modeling).

The remainder of this appendix documents the overall model framework and discusses the integration of individual components into a cohesive model. Section 2 provides a brief overview of the major components of the model and describes how they fit together. Components of the model not covered in the other appendices are also discussed in Section 2. Section 3 describes the interfaces between the major components, presenting the procedures for converting outputs of one model component to inputs for another. In Section 4, the computerization of the model is discussed. The required model inputs and useful model outputs are described in Sections 5 and 6, respectively. Finally, in Section 7, some of the assumptions in the model are highlighted.

This appendix pertains to the model as of February 1, 1984. Because the liner-location risk model is evolving and being updated, the current model differs somewhat from the descriptions given here.

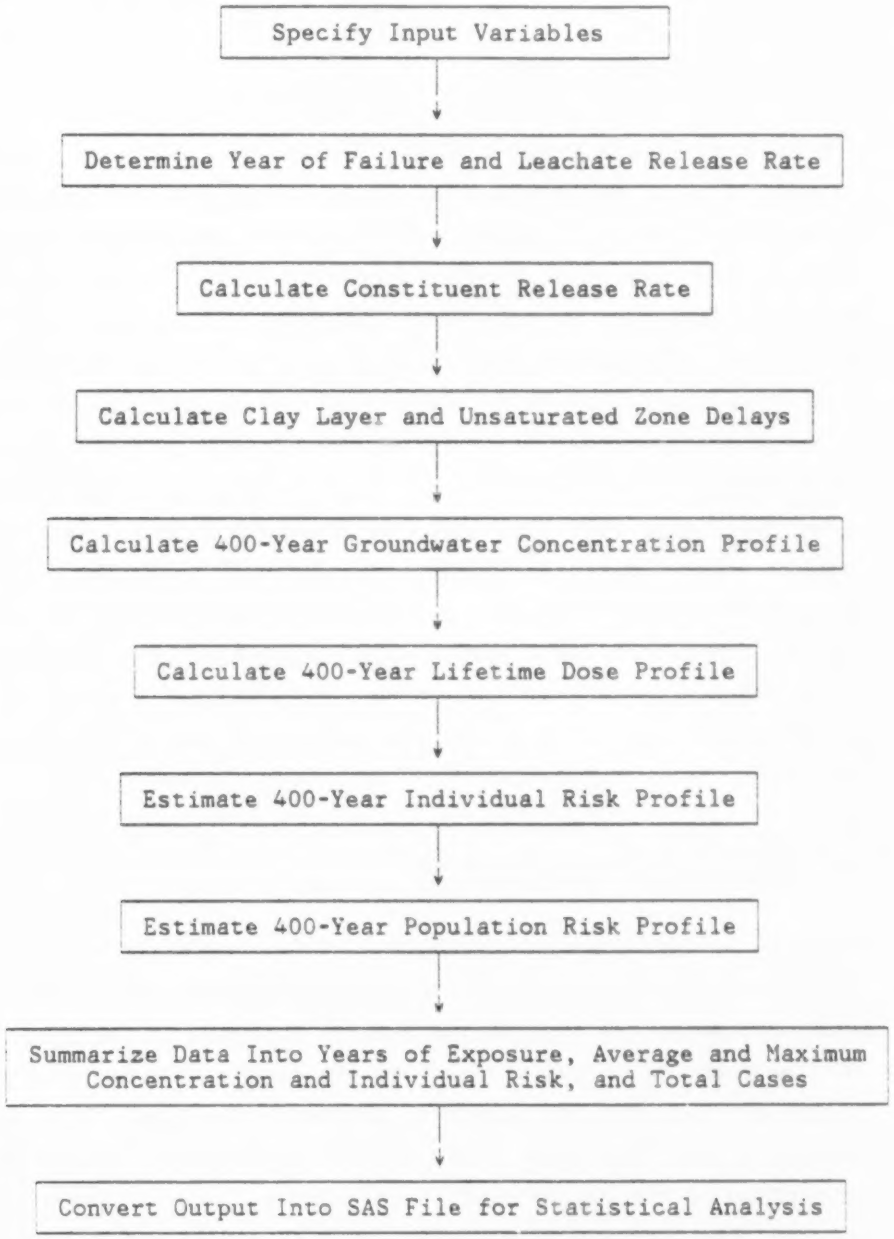
2. OVERVIEW OF LINER-LOCATION RISK MODEL

The liner-location risk model is a sequential combination of algorithms that estimates the human health risks of land disposal of hazardous waste. For any specified set of input variables (e.g., disposal type and design, constituent, groundwater scenario), the model can provide estimates of exposure point chemical concentrations, individual risks, and population risks over the 400-year modeling time horizon. The model has been computerized to facilitate evaluation of risk for numerous combinations of input variables. Hence, the liner-location risk model is a powerful tool for analyzing differences in projected health risk resulting from various land disposal technologies, locations, and wastes. For example, the effects of various liner designs or groundwater transport scenarios on risk estimates can be examined. Thus, the liner-location risk model is well suited to risk comparison among regulatory alternatives.

The complete model is composed of several discrete components that have been linked to allow sequential processing. Figure G-1 is a simplified

FIGURE G-1

CALCULATION SEQUENCE FOR THE LINER-LOCATION MODEL


Specify Input Variables
Determine Year of Failure and Leachate Release Rate
Calculate Constituent Release Rate
Calculate Clay Layer and Unsaturated Zone Delays
Calculate 400-Year Groundwater Concentration Profile
Calculate 400-Year Lifetime Dose Profile
Estimate 400-Year Individual Risk Profile
Estimate 400-Year Population Risk Profile
Summarize Data Into Years of Exposure, Average and Maximum Concentration and Individual Risk, and Total Cases
Convert Output Into SAS File for Statistical Analysis

flow chart showing the linkage of the model components and the logical operational sequence. Brief descriptions of the major components of the liner-location risk model are provided in the following subsections.

2.1 Failure/Release Model

The failure/release model predicts failure probabilities and leachate release volumes over a 200-year period for 24 types of hazardous waste land disposal (10 landfill designs, eight surface impoundment designs, six waste pile designs) and five climate categories (based on net infiltration). The model was developed by Pope-Reid Associates and is described in detail in Appendix A. The actual failure/release model is not incorporated in the liner-location risk model. Instead, the summarized outputs of the failure/release model (i.e., failure probability and release volume for seven benchmark periods for each disposal type and climate category) were converted into a data file that can be accessed by the liner-location model. Thus, for a given climate and disposal type, the predicted failure probabilities over time and release rates given failure at different times can be determined. The release rate is the first key parameter determined in the risk magnitude estimation sequence, and the year of failure (based on failure probability) is the starting point for calculating the timing of the risk.

2.2 Constituent Delay Equations

Facility failure does not necessarily imply immediate release of chemical waste constituents into the saturated groundwater zone. The liner-location model estimates the time period between the year of facility failure and initial entry of a constituent into the saturated zone. Two separate time delays are computed and summed to determine the total. For facility designs with a clay liner, the delay in constituent release resulting from adsorption of the constituent to the clay is computed. For all facility designs, the time period required for the constituent to pass through the unsaturated zone is calculated. The total of these two values, the clay liner delay and the unsaturated zone delay, represents the length of time between facility failure and entry of constituent into the saturated zone.

The clay liner delay applies only to facilities with clay liners and is zero for all other facility designs. The equations for calculating clay delay time were provided by Pope-Reid Associates. The approach is to determine the theoretical adsorption capacity of the liner (mass), then divide that value by the constituent release rate (mass/time). After the liner adsorption capacity is reached, constituent breakthrough is assumed to occur. The calculation algorithm for organics is as follows:

$$\begin{aligned} TIMOA &= OLAC/CMS \\ OLAC &= 0.5 * CM * (Rd - 1) * (0/pc)* \\ &\quad CS * (10^{-6}\ MT/g) \\ CM &= CLT * CLA * pc \\ CMS &= CS * RV * (10^{-9}\ MT/mg) \end{aligned}$$

The additional equations for metals are:

$$\begin{aligned} TIMMA &= MLAC/CMS \\ MLAC &= CM * MEC * (10^{-6} MT/g) \end{aligned}$$

where:

TIMOA = clay delay time, organics (yr)
TIMMA = clay delay time, metals (yr)
OLAC = liner adsorption capacity, organics (MT)
MLAC = liner adsorption capacity, metals (MT)
CMS = constituent release rate (MT/yr)
CM = clay liner mass (MT)
Rd = constituent retardation factor (dimensionless)
0 = clay porosity = 0.5 (dimensionless)
pc = clay density = 1.65 (MT/m^3)
CS = constituent water solubility (mg/1)
MEC = metal-clay exchange capacity (g/MT)
CLT = clay liner thickness (m)
CLA = clay liner area (m^2)
RV = facility liquid release rate (1/yr)

The clay liner area (CLA) is assumed to be equal to the facility surface area, which is an input variable that must be specified. Values for the remaining variables are retrieved from the input data files and a. either constituent-specific (Rd, CS, MEC), design-specific (CLT), or design and climate specific (RV). These equations overestimate the clay delay time (i.e., underestimate the risk) whenever there is significant fracturing or channeling in the clay liner. For this reason, risks for clay liner designs are generally calculated both with and without the clay delay to give plausible upper and lower bounds on the risk.

The unsaturated zone delay is calculated for all input variable combinations analyzed. This delay accounts for the time between release of the constituent to the unsaturated zone and release to the saturated zone (i.e., constituent travel time through the unsaturated zone). The approach, equations, and parameter values used to estimate this time were provided by Geraghty & Miller, Inc. They recommend a modified form of the wetting front model described by McWhorter and Nelson (1979). This model is discussed in greater detail in Appendix B, Subsurface Transport Modeling.

The modified McWhorter-Nelson equation is:

$$t = (L/q)\ (n - \theta_r)\ (q/K)^{x/(2+3x)}(Rd)$$

where

t = constituent travel time (yr)
L = unsaturated zone thickness (m)
q = leakage rate (Darcian flux) at liner (m/yr)
n = soil porosity (dimensionless)
θ_r = initial soil moisture content, assumed to be at field capacity (dimensionless)
K = saturated hydraulic conductivity (m/yr)
x = pore-size distribution index (dimensionless)
Rd = constituent retardation factor (dimensionless)

The leakage rate, q, is calculated by dividing the predicted leachate release rate (m^3/yr) by facility surface area (m^2). Rd is constituent-specific and is retrieved from the input file. The other parameter values used in the equation are given in Figure G-2.

2.3 Groundwater (Saturated Zone) Transport Model

Geraghty & Miller, Inc., selected the approach, models, and parameter values used for the saturated zone transport analysis. The random-walk particle tracking model of Prickett et al. (1981) was used to simulate transport. A full description of the approach to groundwater modeling is given in Appendix B, Subsurface Transport Modeling.

The groundwater transport model itself was not incorporated into the liner-location risk model. Rather, an input file was constructed from the model output generated by Geraghty & Miller. The liner-location model selects the appropriate value from the input file, then adjusts it as required to give either the groundwater concentration or mass loading rate to a surface water body. The groundwater transport model was run for nine groundwater flow scenarios, three distances (between source and exposure point), and three constituent mobility classes over a 200-year simulation period. The outputs, based on a unit mass input, are groundwater concentration and mass loading rate estimates for 200 years for each scenario-distance-mobility class combination. Groundwater scenario, distance, and constituent identification (which determines mobility) are input variables that must be specified for each liner-location model run. Based on these specifications, the liner-location model retrieves the appropriate value.

Retrieval of the correct value for groundwater concentration or mass loading rate for the four multi-layer groundwater flow scenarios (F, G, H, I) requires an additional step. For the single-layer flow scenarios (A, B, C, D, E), only one value is available for each scenario-distance-mobility class combination, and that value is used. Scenario F, which has an aquifer below a non-aquifer, has values only for the aquifer layer. These

FIGURE G-2

PARAMETER VALUES FOR McWHORTER-NELSON EQUATION

Parameter	Aquifers[1]	Non-Aquifers[2]
L(m) - Climates 1, 2	27.5 - FD[3]	15.0 - FD
- Climates 3, 4, 5	5.5 - FD	5.0 - FD
- Real facilities	XL[4] - FD	XL - FD
n	0.25	0.275
θr	0.15	0.25
K (m/yr)	1000	1
x	3.5	1.5

[1] Aquifer defined as flow velocity ≥ 1 m/yr; includes groundwater scenarios A, B, C, D, E, G, H, I.

[2] Non-aquifer flow velocity < 1 m/yr; groundwater scenario F only.

[3] FD = facility depth = 6 m for landfills, 2.1 m for surface impoundments, 0 for waste piles (based on Pope-Reid model facilities).

[4] XL = estimated actual unsaturated zone thickness, determined by Geraghty & Miller, Inc.

values are used in all cases, with the assumption that any well must penetrate the aquifer layer. Scenarios G, H, and I are double-aquifer scenarios, with values for both aquifer layers (scenario I also has an intervening non-aquifer layer). The appropriate layer for well concentrations is determined by comparing the well depth (given in Appendix B for site-visit facilities) with the depth of the boundary between aquifers (sum of unsaturated zone depth and top layer depth and, for Scenario I, half of the intervening layer depth). If the well depth is less than the depth of the boundary between layers, the top layer values are used. Otherwise, the bottom layer values are used. Mass loadings to surface water for scenarios G and H are the sum of the loadings for the two layers. Only the top layer values are used to determine mass loadings for scenario I.

2.4 Exposure Model

The exposure model converts the groundwater concentrations or mass loadings to surface water into chemical doeses to exposed populations. The liner-location risk model is based on the toxic effects of chronic chemical exposures. The risk estimation model (Appendix D) was developed to predict chronic effects and is based on lifetime chemical doses. Therefore, all chemical exposures must be evaluated in terms of lifetime doses. 1/ As a result, the individual chemical concentrations predicted by the model to this point must be transformed to average lifetime exposure levels, then converted to lifetime chemical doses in mg/kg/day. The lifetime dose values are taken as inputs to the next step in the risk analysis sequence, the risk estimation model.

For the groundwater exposure pathway, the starting point for the exposure model is a 400-year groundwater concentration profile. In cases where the

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1/ Exceptions to this are the few chemicals in the data base classified as teratogens. Risks for these chemicals are based on yearly (smallest time increment in the model) doses.

groundwater source contributes to a multi-source water supply, each concentration is multiplied by the water supply fraction to correct for dilution from other sources (assuming concentration in other sources to be zero). The value corresponding to each year represents the estimated drinking water concentration in that year (no effects of water treatment are included). This profile is transformed to a 400-year profile of 70-year-average drinking water concentrations, with 70 years the assumed human life span. This is done by averaging each yearly concentration with the 69 immediately preceding yearly concentrations (i.e., calculating a 70-year moving average for all 400 years). The concentration is assumed to be zero for the 69 years preceding facility start-up. Therefore, each value in the transformed profile represents the average concentration that a 70-year-old person would have been exposed to in their lifetime. These moving average concentrations are the most appropriate values to use in lifetime dose and risk calculations. The unaveraged yearly concentrations are inappropriate as they do not represent lifetime exposures (although, in some cases, average risks can be calculated for non-threshold toxicants from the yearly concentrations alone). A single 400-year (or any other period) average concentration would greatly limit the type and accuracy of possible risk estimates.

There are several advantages to using 70-year moving averages as a measure of exposure instead of individual yearly concentrations or single period averages, including:

- Allows risk calculations for threshold (i.e., non-linear response with effects threshold) chemicals;
- Allows proper distribution of both threshold and non-threshold risks over time;
- Allows proper calculation of risk magnitude over time, and accurate estimation of values such as maximum, median, and various percentile risks;
- Allows proper estimation of risk variance;

- Allows incorporation of a dynamic population model into the population risk calculation; and

- Allows incorporation of other time-dependent variables which affect does (e.g., water supply fraction, treatment efficiency, corrective action) or population.

The 70-year moving average approach to exposure estimation increases the flexibility of the liner-location model in terms of future refinements. This approach more realistically reflects the toxicology of chronic exposures and more accurately represents the time element in the risk analysis.

The 70-year average concentration profile is converted to a lifetime does profile by factoring in drinking water intake and body weight. (Concentration and dose are related by a time-independent, linear factor. Thus, this conversion can be made before or after averaging.) Average human drinking water consumption was assumed to be 2 liters/day (EPA, 1980; NRC, 1977), and average human body weight was assumed to be 60 kg (NIOSH, 1983; average of male and female). Thus, the constant factor for converting mg/l in drinking water to mg/kg/day dose was 0.033 l/kg/day (2 l/day ÷ 60 kg). The program multiplies each 70-year average concentration in the 400-year period by this conversion factor to give a lifetime dose for each year. The dose value for each year corresponds to the lifetime dose of an individual reaching 70 years of age in that year. The lifetime doses are the input to the risk estimation equation, which, for a given dose, estimates the probability and type of effect.

The surface water exposure model is similar to the groundwater exposure model, with one additional step required. The groundwater transport model projects annual mass loading rate to a surface water body. This rate is first converted to a surface water concentration, and from that point on, the surface water exposure model parallels the groundwater model. Conversion of the annual mass loading rate to an average annual concentration is based on dilution only. For rivers and streams, the model divides mass loading (mg/yr) by average annual flow (l/yr), yielding average concentration (mg/l). Clearly, this conversion is a simplification that assumes complete mixing prior to withdrawal, no stratification within the water body, and no removal (degradation, adsorption, volatilization) over time.

Based on the relationship between concurrent mass loadings and groundwater concentrations predicted by the transport model for the highest-flow groundwater scenario at a large facility, a low-flow stream (10^{11} liters/year) will dilute the constituent concentration at least 10 times relative to groundwater. A lower groundwater flow or larger stream would result in a correspondingly larger difference. Thus, in most cases the risks via groundwater would swamp the risks via surface water if both exposure pathways exist. Risks from surface water exposure pathways may be important, however, at sites with no groundwater exposure or for certain bioaccumulating chemicals.

2.5 Risk Estimation Model

The general approach, equations, and parameter values used to estimate chemical-specific risks of a given dose were provided by Environ Corporation and are discussed in detail in Appendix D. The generalized risk equation that applies to both threshold and non-threshold chemicals is:

Risk = individual lifetime probability of toxic effect
H = unit risk (risk per unit dose) $(\text{mg/kg/day})^{-K}$
S = scaling factor
K = dose-response parameter
D = lifetime dose (mg/kg/day)

H, S, and K are chemical-specific factors describing the toxic response to that chemical. Each chemical also has a designated toxic effect on which the quantitative parameters are based (cancer for all carcinogens; for other chemicals, the effect occurring at lowest chronic dose levels). All of the components and algorithms of the liner-location model described previously (e.g., failure/release model, groundwater transport model) are necessary to determine the lifetime chemical dose, D.

In some cases the individual risk calculated by the model may be greater than 1.0. This results from the combination of two factors:

- The risk estimation equation is a low-dose equation and is not valid for high doses. For carcinogens ($K = 1$), the model is linear and does not take into account non-linear response at high doses. For non-carcinogens ($K \geq 1$), the model is quadratic but only applies to doses below the experimental minimum effective does (i.e., valid for risks less than 10 percent).

- Exposures are likely substantially overestimated due to a number of conservative assumptions in the various models leading to the dose estimate. This results in doses that, in some cases, exceed the valid dose range of the risk estimation equation.

Given the risk estimation model, predicted individual risks greater than 0.1 should only be interpreted qualitatively as indicative of very high chronic risks.

Using the given equation, the model calculates individual lifetime risks for each of the 400 model years, constructing a 400-year chronic risk profile. Estimating individual risks for a selected combination if input variables is the primary objective of the liner-location risk model. Thus, the individual risk profile is a key model output.

The final major step in the model sequence is the estimation of population risk. This is calculated by multiplying the estimates of individual risk and exposed population size for each model year, yielding a 400-year population risk profile. The exposed population for each year is the number of people reaching 70 in that year (i.e., the number of people receiving their full lifetime dose as of that year, assuming a 70-year life span). There is currently no net population change over time in the model, with the initial population size assumed to remain constant through the modeling period. Therefore, assuming uniform age distribution, the exposed population for any given year is (1/70) times the initial population. Initial populations-at-risk for site-visit facilities are given in Appendix C.

3. INTERFACES BETWEEN MAJOR COMPONENTS

This section describes the important linkages between major model components. The focus is on the interfaces between the release and groundwater transport components and between the groundwater transport and exposure components. These two linkages require the most explanation because several adjustments were necessary to convert output of the first component into usable input for the second. These adjustments are documented below.

3.1 Release Model-Groundwater Transport Model Interface

The failure/release model provides a failure probability and release volume for seven benchmark periods for 24 facility designs and five climate categories. Thus, there are 120 design scenarios, each having failure and release estimates for seven time periods. These failure/release model outputs are stored in a liner-location input file.

3.1.1 Using the Release Model Output

Because of the desire to limit the computation time (and amount of output) for each model run during the initial model development phase, a single year of failure was selected for each climate-design combination. This limited each model run to a single risk estimate, but also limits the incorporation of probabilistic notions in the model. The midpoint of the benchmark period in which the failure probability first exceeds 1 percent is assumed to be the year of failure. For example, if failure probability is 0.005 for the 10-year benchmark and 0.04 for the 20-year benchmark, the year of failure in the model would be year 15. It would also be 15 if the failure probability is 0.99 for the 20-year benchmark, and the model would not distinguish these cases. Alternatives to this approach that fully incorporate the stochastic nature of failure are being investigated as part of the ongoing model development work.

The choice of one percent was somewhat arbitrary; in fact, a 10 percent cutoff was first considered, but many climate-design combinations have no failure within 200 years under this rule. Under the 1 percent rule, there is at least 99 percent probability that an individual prediction of no failure is correct. However, the probability that a prediction of failure is correct varies from 1 to 100 percent, with all probabilities from 1 to 100 percent treated similarly.

Although the one percent rule is somewhat arbitrary, it was a simple way to incorporate, at least partially, the probabilistic nature of failures into the model, given the constraints of data availability and the desire to limit model runs and output. Risks estimated under this rule do not represent the absolute or total risk associated with a facility. They are instead risk measures that can be used to compare risks of different design, location, and waste scenarios on a consistent basis.

The liner-location model estimates annual leachate release volume for a given climate-design combination by dividing the 200-year cumulative volume by the number of years of release (i.e., 200 minus year of failure). Thus, the same total leachate volume is predicted regardless of the year of failure, with higher annual releases or the year of failure, is larger. For example, if the year of failure is 75 and the 200-year cumulative release volume is 1,000,000 liters, the annual release rate after failure would be:

$$1,000,000/(200 - 75) = 8000 \text{ liters/year.}$$

The estimated release rate is assumed to remain constant from the year of failure to year 200, the end of the failure simulation period.

3.1.2 Scaling Release Volumes

The release model outputs are based on hypothetical facilities of a specified size. Thus, projected leachate release rates must be adjusted to compensate for size differences between the model facility and the specific facility being evaluated. This was done on a surface area basis for all land technology types and designs as follows:

$$RR_r = RR_m\ (SA_r/SA_m)$$

where:

RR_r = real facility release rate (l/yr)

RR_m = model facility release rate (l/yr)

SA_r = real facility surface area (m^2)

SA_m = model facility surface area (m^2)

It is assumed that failure probability is independent of facility surface area, an assumption that appears reasonable on the basis of preliminary studies (Pope-Reid Associates, Inc., 1984).

3.1.3 Converting Leachate Release to Constituent Release

The next step in the model sequence is the estimation of release rates of specific chemicals based on the scaled leachate (liquid) release rates predicted. The constituent release rate is an important determinant of risk. A key simplification in the liner-location risk model is the assumption that chemical waste constituents are released continuously in the leachate at concentrations equal to their water solubility. The model assumes that release continues until the constituent mass in the facility is depleted. There are two problems immediately apparent in this approach:

- It accounts only for releases resulting from constituents being dissolved and transported by the water component of the leachate. It ignores the non-water component of the leachate, which may contain the constituents as free liquids at high concentrations. However, this underestimate may not be as drastic as it first appears because (1) the water component of the leachate is generally much greater fraction than the non-water component, and (2) most of the liquids in the data base are at least moderately soluble. The release underestimate applies primarily to landfills and is most severe for liquids with very low water solubility and present in the facility in large volumes.

- It assumes constituents are present at their theoretical water solubility, whereas in fact the overall solute concentration may vary considerably. For example, in unlined landfills only a small fraction of the infiltrating water may actually contact the constituent, resulting in an overall leachate concentration much less than the predicted based on solubility.

Thus, the assumption of constituent release at solubility increases the uncertainty of the constituent release rate estimates, but it is probably a reasonable first-cut simplification. Improved approaches to estimating constituent release are being investigated in Phase II of the liner-location model development.

A yearly mass balance of the amount of constituent present in the facility is maintained during model operation. Constituent release ends when the mass is depleted, ensuring that the released amount is not greater than in input amount. The annual input mass of constituent is determined for real facilities (or specified for hypothetical facilities), and the mass balance algorithm adds this amount for each year of facility operation (assumed to be 20 in the model). It also subtracts the amount released during each model year, maintaining a balance that is the maximum release amount for that year.

The adjustments to the failure/release model estimates described in this section convert the output of that model into the required input, in the proper form, for the groundwater transport model. At this point, the model has estimated the annual mass loading of constituent (kg/yr) to the groundwater system.

3.2 Groundwater Transport Model-Exposure Model Interface

The groundwater transport model provides, for nine flow scenarios, three distances, and three constituent mobility classes (81 possible combinations), groundwater concentrations and surface water mass loading rates for 200 years following a unit mass input of 1 kg/yr. Because the liner-location risk model is based on a one-year time increment and the output of the groundwater transport model was in variable time increments (varied from 0.02 to 5.0 years), a format adjustment was necessary. The conversions were done as follows:

1) Converting Values for Shorter Periods to Yearly Values - Yearly concentrations were estimated by averaging all values within the year. Yearly mass loading rates were determined by summing the rates for all time periods within the year.

2) Converting Values for Longer Periods to Yearly Values - Yearly concentrations were estimated by linear interpolation. Yearly mass loading rates were estimated by dividing the total rate for the time period by the number of years in the time period.

A liner-location input file was constructed from the converted values, with values (often zero) corresponding to years 1 through 200. This format adjustment was only necessary once, following initial receipt of the groundwater transport model output from Geraghty & Miller.

3.2.1 Scaling Groundwater Model Outputs

Scaling is required to adjust the groundwater model outputs for varying constituent mass input and facility size. The groundwater model predicts groundwater concentrations for a unit mass input, 1 kg/yr, and from a defined rectangular source, 1 meter wide and 10 meters long. The method for scaling the output was recommended by Geraghty & Miller and is described in Appendix B. The scaling factor reduces to the following expression:

$$\mathrm{SFAC} = \left| \frac{L}{10\mathrm{m}} \right| \left| \frac{M_I/SA}{0.1\ \mathrm{kg/yr/m^2}} \right|$$

where

SFAC = scaling factor (dimensionless)
L = facility length (meters)
M_I = constituent mass input rate (kg/yr)
SA = facility surface area (m²)

If the facility dimensions are unknown, the model assumes that the facility is square (i.e., $L = SA^{.5}$). Each projected groundwater concentration or mass loading rate is multiplied by the scaling factor. The surface water mass loading rates are multiplied by an additional adjustment factor, facility width, because the scaled rates are for a one-meter wide strip. Essentially, the scaling factor for surface water mass loading reduces to M_I, constituent mass input.

3.2.2 Summation of Predicted Concentrations Over Time

The scaled groundwater transport model output is for individual release years. The concentrations at an exposure point over time usually result from releases over several years. Exposure point concentrations are derived by summing, for each of the 400 model years, the predicted concentrations resulting from each previous year. If, for example, releases occur in years 50, 51, and 52 and the predicted concentrations in year 75 from these releases are 0.05, 0.2, and 1.0 mg/l, the total concentration in year 75 would be 1.25 mg/l. This summation process is described in Geraghty & Miller's appendix on groundwater transport

(Appendix B). The result of this summation is a 400-year groundwater concentration profile.

3.2.3 Accounting for Constituent Degradation

Although many substances are very persistent in groundwater, some are known to decay over time. Concentrations of the data base constituents with documented half-lives in groundwater (as shown in Appendix F, Figure F-5) are adjusted by the model to account for this degradation. It is assumed that the degradation kinetics are first-order and that degradation occurs from the time of constituent release from the disposal facility to the time it is withdrawn for use. Thus, for degradable constituents, concentration is calculated as follows:

$$C_t = Co\ (\exp^{-\lambda t})$$

where:

C_t = concentration adjusted for t years of degradation (mg/l)

Co = scaled concentration predicted by groundwater transport model (mg/l)

λ = decay constant = 0.69/half-life (yr^{-1})

t = years of degradation = clay decay + unsaturated zone delay + saturated zone delay (yr)

This factor is applied to each yearly concentration predicted for each release year. Because the factor is time-dependent, it cannot simply be applied to the summed concentration curve for each year. Although the groundwater half-lives used are based on saturated zone degradation, they are also used to estimate decay in the clay layer and unsaturated zone. However, because degradation is probably more rapid in these layers, this is only a minimum estimate of the overall degradation, which may be considerably higher. Also, no degradation is assumed prior to the year of failure. This same approach to estimating degradation is used to adjust the mass loading to surface water.

3.2.4 Solubility Check

A final step in the adjustment of the groundwater model results is to compare the predicted constituent concentration with its water solubility. The lower of the two values is then taken as the concentration used as input to the exposure model. This is necessary because the groundwater transport model does not account for the leachate input volume resulting from facility failure. Therefore, in some situations where a very soluble chemical is released at a high rate into a low-flow groundwater scenario, the liner-location model predicts the groundwater concentration to be higher than solubility. The model sets these concentrations equal to the solubility concentration. Thus, the modeled exposure concentrations can never exceed water solubility.

At this point, the model has estimated either the constituent concentration over 400 years in groundwater or the 400-year mass loading to surface water. This is the necessary input to the exposure model.

4.0 COMPUTERIZATION OF THE MODEL

To provide a feasible method for estimating risks resulting from a large number of disposal options, the liner-location risk model was computerized. This allows rapid computation of the complex algorithms that make up the model, permitting detailed analysis of many different combinations of input variables in a short time period. The maximum number of computations executed by the program during analysis of a single case (i.e., input variable combination) is approximately 100,000. Thus, the need for computerization is evident. The major phases in the computerization of the liner-location model are outlined in this section.

4.1 Input Files

The first phase in the computerization of the model was the organization of the input files, which were designed to provide the most efficient use of information within the programming framework. There are essentially two types of files in the model: files containing constant information and files containing variable information.

4.1.1 Constant Information Files

This category includes files whose contents do not change during operation. These data are stored in computer memory for retrieval at any point in the program. These files are:

- The facility file, which contains data on the 70 site-visit disposal facilities. Data include:
  - location (latitude and longitude)
  - hydrogeologic scenario
  - climate category
  - population served by groundwater (up to 3 populations)
  - distance from facility to wells
  - well depths
  - fraction of water supply provided by wells
  - population served by surface water
  - distance from facility to surface water
  - surface water flow
  - distance to downstream drinking water intakes
  - fraction of water supply provided by surface water
- The wastestream file, which stores the identities and annual mass inputs of the constituents of concern at each site-visit facility.
- The constituent file, which contains data on the 45 constituents of concern in the model. The stored data are:
  - water solubility
  - decay constant

- retardation factor
- mobility class
- unit risk (H)
- scaling factor (S)
- dose-response parameter (K)
- bioconcentration factor
- type of toxic effect

- The release file, which contains data developed by Pope-Reid Associates estimating failure probabilities and total release volumes for model waste disposal facilities. Data are provided for seven selected benchmark periods (up to 200 years) under five climatic conditions for:
  - 10 landfill designs
  - 8 surface impoundment designs
  - 6 waste pile designs
- The groundwater transport scenario file, which contains data developed by Geraghty & Miller, Inc. to simulate groundwater transport given a combination of hydrogeologic setting, constituent mobility class and distance to groundwater well or surface water body. For each year in the modeling period (up to 200), the file contains:
  - projected groundwater concentration
  - projected mass loading to surface water
- The facility size file, which has data on the size of the site-visit facilities.

4.1.2 Variable Information File

This file contains the variable input information necessary to operate the program. These specifications differ between model runs, and this file is developed based on the requirements of the analysis being done. The file is read sequentially by the program and provides the link between all input files. The file includes:

- A facility number identifying the facility to be processed.
- A disposal type identifying the appropriate disposal technology (landfill, surface impoundment, waste pile) and design.
- Constituent numbers identifying the constituents disposed at the facility.
- Constituent amounts giving the yearly amount disposed (in kg) of the constituents of concern.

Once the facility and constituents being processed have been established, the logical flow of the computer model can proceed.

4.2 Program Logic and Operation

The second phase of computerizing the liner-location risk model was design of the general program logic. Every computer program contains three basic logical structures--operational sequence, selection, and repetition.

The operational sequence consists of a series of actions performed one after another. It is the most basic of structures, a simple transition from point A to point B. The selection or alternation structure offers greater flexibility. The computer can select either of two alternatives based on a predetermined set of conditions. This structure enables branching at different points in the program. The repetition structure is a powerful tool involving the construction and use of loops for repeating operations that are to be performed many times over. The same process can be reiterated countless times without having to repeat the programming code.

4.2.1 Loop Structure

The liner-location computer model relies heavily on the looping process, more specifically on nested loops. A nested loop is a loop that is contained completely within the range of another loop.

Figure G-3 illustrates the basic logical flow of the computer model. First, all the constant input files are read and stored in computer memory. The first record of the sequential file is then read. It contains information on the facility to be processed. All facilities included in a specific run are processed until no more facilities are encountered, at which point the program terminates. This repetitive processing of each facility represents the outermost loop in the computer model (loop I in Figure G-3).

For each facility, the model considers two possible routes through which populations can be exposed to toxic constituents. The first is through groundwater ingestion (from a well), and the second is through drinking water ingestion from surface water sources. If the data included in the facility file indicate groundwater exposure, the groundwater model is used. Similarly, if the data indicate surface water exposure, the surface water model is used. A switch in the program determines which model is selected at various junctures.

The next step is to process all toxic constituents present at each facility (loop II). Once a constituent and facility combination is known, the information stored in the facility and constituent constant input files can be accessed.

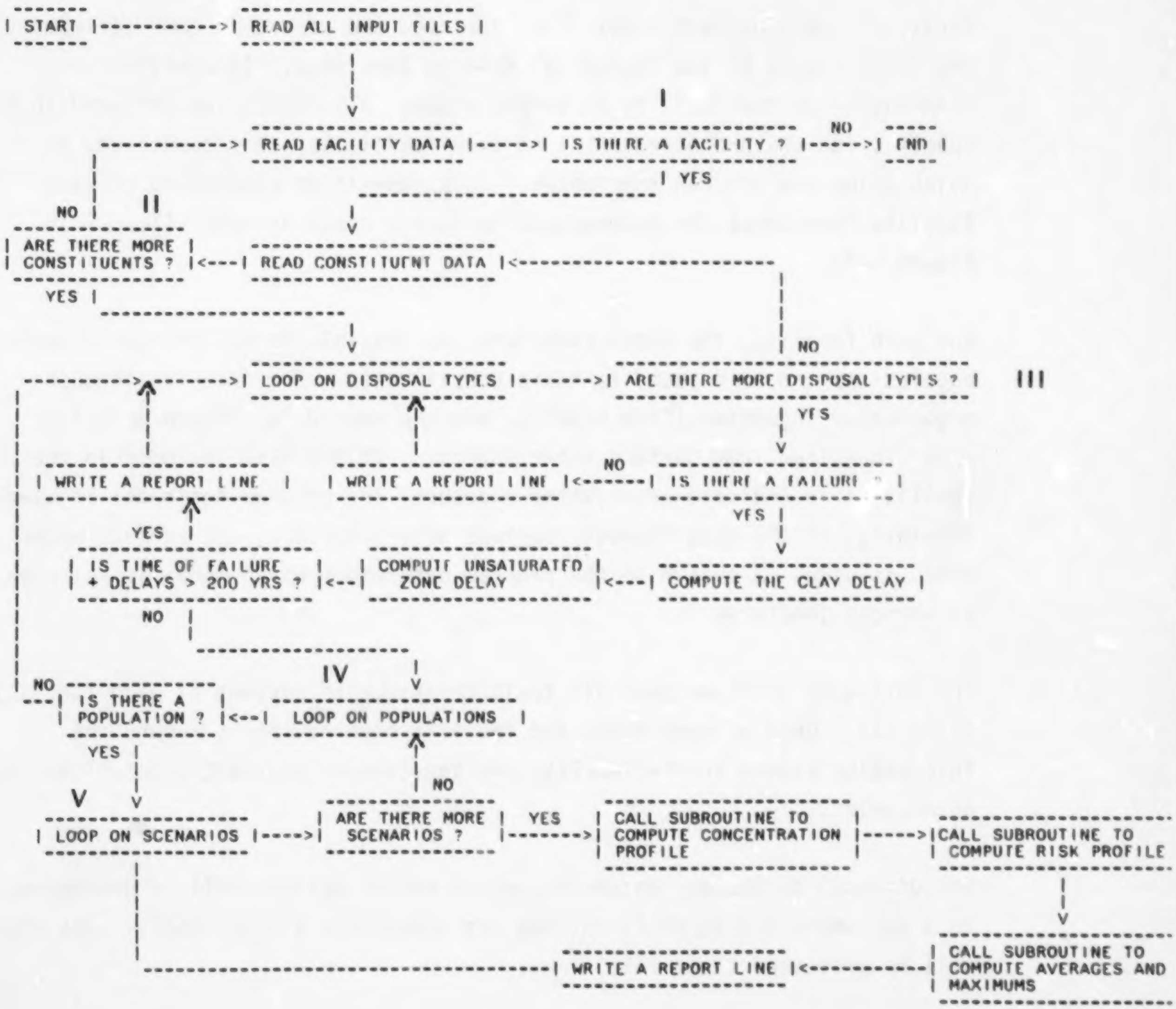
The disposal technology determines which set of designs will be processed. In a run where all landfill options are specified, all 10 landfill designs will be processed (loop III).

After a disposal type design is determined, the program checks the failure rate for that design and climate combination. If the failure rate is less

FIGURE G-3

FLOW DIAGRAM FOR LINER-LOCATION RISK MODEL COMPUTER PROGRAM

Reproduced from best available copy.


START
READ ALL INPUT FILES
I
READ FACILITY DATA
IS THERE A FACILITY ?
NO
END
YES
NO
II
ARE THERE MORE CONSTITUENTS ?
READ CONSTITUENT DATA
YES
NO
LOOP ON DISPOSAL TYPES
ARE THERE MORE DISPOSAL TYPES ?
III
YES
WRITE A REPORT LINE
WRITE A REPORT LINE
NO
IS THERE A FAILURE ?
YES
YES
IS TIME OF FAILURE + DELAYS > 200 YRS ?
COMPUTE UNSATURATED ZONE DELAY
COMPUTE THE CLAY DELAY
NO
IV
NO
IS THERE A POPULATION ?
LOOP ON POPULATIONS
YES
NO
V
LOOP ON SCENARIOS
ARE THERE MORE SCENARIOS ?
YES
CALL SUBROUTINE TO COMPUTE CONCENTRATION PROFILE
CALL SUBROUTINE TO COMPUTE RISK PROFILE
CALL SUBROUTINE TO COMPUTE AVERAGES AND MAXIMUMS
WRITE A REPORT LINE

than 1 percent in all benchmark periods, it is assumed that there is no failure for that disposal option. A report line is printed to show the facility, constituent, and disposal type design and reflect the fact that there was no failure. If there is more than a 1 percent chance of failure in any of the benchmark periods, the midpoint of the earliest benchmark period exceeding 1 percent is assumed to be the year of failure. For all designs having a failure within 200 years, the appropriate release volume is taken from the release file.

Once the year of failure and release volume are determined, the program computes a clay delay time for those disposal designs that include a clay liner. Following this, the program calculates an unsaturated zone delay time, which represents the time for the constituent to pass through the unsaturated zone. If the addition of time of failure, clay delay and unsaturated zone delay exceeds 200 years, the modeling horizon has been exceeded. In these cases, a report line is printed showing time of failure, clay delay time, unsaturated zone delay time, and total elapsed time. No further information is processed, and the program goes to the next disposal option. If, however, the total elapsed time is less than 200 years, the program processes the applicable groundwater transport scenarios.

The model allows for up to three separate exposed populations adjacent to the waste disposal facility. The program contains a loop around the populations (loop IV). If, for example, two different populations are served by different wells, the groundwater transport scenarios that determine the constituent's concentration at the well may not be the same because the two wells may be located at different distances from the point of release.

The last loop (loop V) is around the applicable groundwater transport scenarios. Scenarios are selected based on the hydrogeologic setting applicable to the specific facility, the mobility class of the specified constituent, and the distance from the facility to the well or to the surface water body. The selection of scenarios constitutes the last major logical step in the main program.

4.2.2 Subroutines

For each combination of facility, constituent, disposal type design, population, and groundwater transport scenario, the program calls three subroutines. The first subroutine computes the concentration profile at a well (groundwater model) or in a stream (surface water model). For each year of constituent release into groundwater, an individual concentration profile over time is computed. The individual concentration profile consists of yearly concentration values for up to 200 years. After all the concentrations resulting from every year of release (up to 200) are calculated, the program sums for all 400 model years the concentrations resulting from each release year. The result is a total concentration profile over time. Figure G-4 illustrates the procedure for summing yearly concentrations from different release years.

The second subroutine computes the individual and population risk profiles. For each constituent, a 70-year moving average concentration is calculated as the basis of the dose estimate (assumption of a 70-year lifetime). Individual risk is computed in each of the 400 modeling years to reflect the risk incurred by an individual exposed for the previous 69 years. The population risk is then estimated for each year based on the number of people exposed.

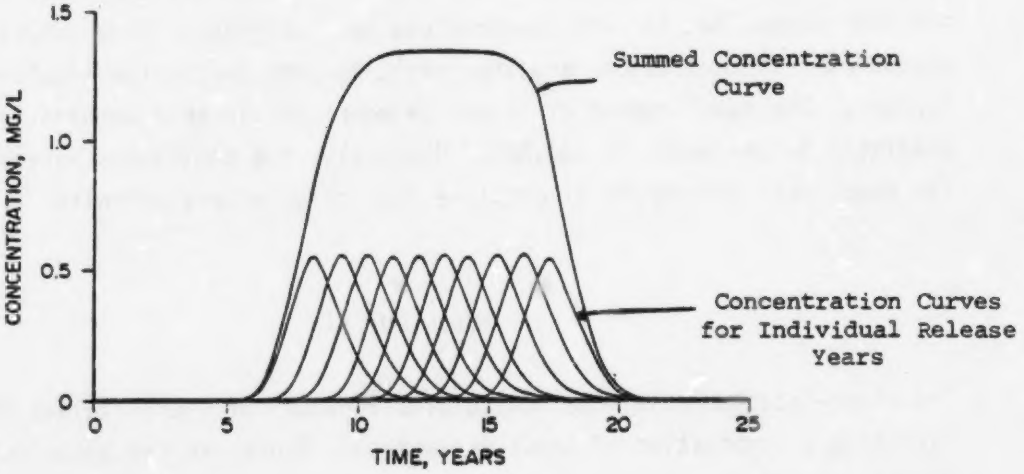
The third subroutine summarizes the information produced by the program for report printing purposes. This subroutine also computes average and maximum constituent concentration and risk values and sums the population risk over the modeling period.

5. MODEL INPUTS

A number of site-specific input variables must be specified before using the liner-location risk model. These variables are identified and described in this section. Some of the variables are continuous (may choose any value) and some are categorical (must choose one of the

FIGURE G-4

SUMMATION OF INDIVIDUAL BREAKTHROUGH CURVES



Source: Derived from Figure 10, Appendix C to this report (Geraghty & Miller, Inc.)

categories available). In analyses of specific facilities, such as the site-visit facilities, many of these variables can be determined based on site-specific data. For analysis of hypothetical facilities, the desired combination of input variables must be specified. Figure G-5 lists the input variables that must be specified for the liner-location risk model.

Part of the value of the liner-location risk model is in the variety of input variable combinations that can be analyzed. There are 6,000 "live" combinations of categorical input variables alone for constituents in mobility class 1; 3,120 combinations for mobility class 2; and 1,680 combinations for mobility class 3. The number of combinations differs because not all groundwater scenarios and distances are available for all mobility classes. Actually, all 6,480 possible combinations exist for each mobility class, but for all combinations not designated "live" above, the groundwater concentration, and thus risk, is zero during the modeling time horizon. The total number of "live" categorical variable combinations available in the model is 164,880. Obviously, the continuous variables in the model make the number of possible risk calculations infinite.

6. MODEL OUTPUTS

The liner-location risk model calculates a number of useful values for each case (i.e., combination of input variables). There are two basic output formats for displaying the result of a model run. The 400-year format, illustrated in Figure G-6, gives the full 400-year profiles for six important output variables: leachate release rate (l/yr), constituent release rate to the saturated zone (kg/yr), groundwater or surface water concentration (mg/l), 70-year moving average groundwater or surface water concentration (mg/l), individual lifetime risk (probability), and population risk (number of cases). The combined unsaturated zone and clay delay time can also be determined by comparing the first year of leachate release (i.e., year of facility failure) with the first year of constituent entry into the saturated zone. In addition to clearly showing the predicted values of each variable, this format elucidates the time

FIGURE G-5

LINER-LOCATION RISK MODEL INPUT VARIABLES

Input Variable	Variable Type	Available for Site-Visit Facilities
Constituent Identity	Categorical (45)[1]	Yes
Constituent Annual Mass Input	Continuous	Yes
Facility Design Type	Categorical (24)	Partial-Major Categories Only
Facility Surface Area	Continuous	Yes
Climate	Categorical (5)	Yes
Unsaturated Zone Thickeness	Continuous	Yes
Groundwater Flow Scenario	Categorical (9)	Partial
Exposure Route	Categorical (2)	Yes
Number of/Distance to Exposure Point	Categorical (3)	Yes
Water Supply Fraction at Each Exposure Point	Continuous	Yes
Size of Exposed Population of Each Exposure Point	Continuous	Yes
Flow Rate for Each Surface Water Exposure Point	Continuous	Yes
Well Depth for Each Groundwater Exposure Point	Continuous	Yes

---

[1] Number of categories given in parentheses.

FIGURE G-6

400-YEAR OUTPUT FORMAT

```
                                                                                        LIFETIME
                                                                        70-YR          RISK TO AN
 YEAR   LEACHATE(L)     CONSTITUENT (KG)   WELL CONCT (MG/L)   AVERAGE CONCT(MG/L)     INDIVIDUAL     NUMBER OF CASES
------  ------------    ----------------   -----------------   -------------------   --------------   ---------------
  50    0.0                   0.0                0.0                 0.0                  0.0               0.0
  51    0.0                   0.0                0.0                 0.0                  0.0               0.0
  52    0.0                   0.0                0.0                 0.0                  0.0               0.0
  53    0.0                   0.0                0.0                 0.0                  0.0               0.0
  54    0.0                   0.0                0.0                 0.0                  0.0               0.0
  55    0.0                   0.0                0.0                 0.0                  0.0               0.0
  56    0.0                   0.0                0.0                 0.0                  0.0               0.0
  57    0.0                   0.0                0.0                 0.0                  0.0               0.0
  58    0.0                   0.0                0.0                 0.0                  0.0               0.0
  59    0.0                   0.0                0.0                 0.0                  0.0               0.0
  60    0.0                   0.0                0.0                 0.0                  0.0               0.0
  61    0.0                   0.0                0.0                 0.0                  0.0               0.0
  62    0.0                   0.0                0.0                 0.0                  0.0               0.0
  63    0.0                   0.0                0.0                 0.0                  0.0               0.0
  64    0.0                   0.0                0.0                 0.0                  0.0               0.0
  65    0.0                   0.0                0.0                 0.0                  0.0               0.0
  66    0.0                   0.0                0.0                 0.0                  0.0               0.0
  67    0.0                   0.0                0.0                 0.0                  0.0               0.0
  68    0.0                   0.0                0.0                 0.0                  0.0               0.0
  69    0.0                   0.0                0.0                 0.0                  0.0               0.0
  70    0.0                   0.0                0.0                 0.0                  0.0               0.0
  71    0.0                   0.0                0.0                 0.0                  0.0               0.0
  72    0.0                   0.0                0.0                 0.0                  0.0               0.0
  73    0.0                   0.0                0.0                 0.0                  0.0               0.0
  74    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  75    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  76    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  77    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  78    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  79    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  80    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  81    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  82    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  83    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  84    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  85    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  86    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  87    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  88    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  89    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  90    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  91    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  92    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  93    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  94    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  95    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  96    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  97    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  98    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
  99    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
 100    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
 101    0.58320E+06           0.0                0.0                 0.0                  0.0               0.0
```

FIGURE G-6
(Continued)

400-YEAR OUTPUT FORMAT

```
  YEAR      LEACHATE(L)     CONSTITUENT (KG)   WELL CONCT (MG/L)         70-YR            LIFETIME      NUMBER OF CASES
                                                                  AVERAGE CONCT(MG/L)    RISK TO AN
                                                                                         INDIVIDUAL
--------   ------------     ----------------   -----------------  -------------------   ------------    ---------------
  102       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  103       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  104       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  105       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  106       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  107       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  108       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  109       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  110       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  111       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  112       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  113       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  114       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  115       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  116       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  117       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  118       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  119       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  120       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  121       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  122       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  123       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  124       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  125       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  126       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  127       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  128       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  129       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  130       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  131       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  132       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  133       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  134       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  135       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  136       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  137       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  138       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  139       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  140       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  141       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  142       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  143       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  144       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  145       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  146       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  147       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  148       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  149       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  150       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  151       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  152       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
  153       0.58320E+06          0.0                 0.0                 0.0                0.0               0.0
```

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FIGURE G-6
(Continued)

400-YEAR OUTPUT FORMAT

```
                                                                                    LIFETIME
                                                                       70-YR      RISK TO AN
 YEAR    LEACHATE(L)     CONSTITUENT (KG)   WELL CONC. (MG/L)  AVERAGE CONC.(MG/L)  INDIVIDUAL   NUMBER OF CASES
 ----    -----------     ----------------   -----------------  -------------------  ----------   ---------------
 154     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 155     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 156     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 157     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 158     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 159     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 160     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 161     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 162     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 163     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 164     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 165     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 166     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 167     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 168     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 169     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 170     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 171     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 172     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 173     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 174     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 175     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 176     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 177     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 178     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 179     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 180     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 181     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 182     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 183     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 184     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 185     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 186     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 187     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 188     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 189     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 190     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 191     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 192     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 193     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 194     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 195     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 196     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 197     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 198     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 199     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 200     0.58320E+06         0.0                 0.0                0.0               0.0            0.0
 201     0.0                 0.0                 0.0                0.0               0.0            0.0
 202     0.0                 0.0                 0.0                0.0               0.0            0.0
 203     0.0                 0.0                 0.0                0.0               0.0            0.0
 204     0.0                 0.0                 0.0                0.0               0.0            0.0
 205     0.0                 0.0                 0.0                0.0               0.0            0.0
```

FIGURE G-6
(Continued)

400-YEAR OUTPUT FORMAT

```
                                                                      70-YR             LIFETIME
 YEAR   LEACHATE(L)   CONSTITUENT (KG)   WELL CONCT (MG/L)   AVERAGE CONCT(MG/L)   RISK TO AN      NUMBER OF CASES
                                                                                    INDIVIDUAL
 ----   -----------   ----------------   -----------------   -------------------   ------------    ---------------
 206        0.0             0.0                0.0                 0.0                0.0               0.0
 207        0.0             0.0                0.0                 0.0                0.0               0.0
 208        0.0             0.0                0.0                 0.0                0.0               0.0
 209        0.0             0.0                0.0                 0.0                0.0               0.0
 210        0.0             0.0                0.0                 0.0                0.0               0.0
 211        0.0             0.0                0.0                 0.0                0.0               0.0
 212        0.0             0.0                0.0                 0.0                0.0               0.0
 213        0.0             0.0                0.0                 0.0                0.0               0.0
 214        0.0             0.0                0.0                 0.0                0.0               0.0
 215        0.0             0.0                0.0                 0.0                0.0               0.0
 216        0.0             0.0                0.0                 0.0                0.0               0.0
 217        0.0             0.0                0.0                 0.0                0.0               0.0
 218        0.0          4782.23828            0.0                 0.0                0.0               0.0
 219        0.0          4782.23828            0.0                 0.0                0.0               0.0
 220        0.0          4782.23828            0.0                 0.0                0.0               0.0
 221        0.0          4782.23828            0.0                 0.0                0.0               0.0
 222        0.0          4782.23828            0.49233228          0.00703332         0.00002553        0.00036473
 223        0.0          4782.23828            4.26040173          0.06789619         0.00024646        0.00352090
 224        0.0          4782.23828           15.2236996           0.28537750         0.00103592        0.01479884
 225        0.0          4782.23828           33.8482971           0.76892459         0.00279120        0.03987423
 226        0.0          4782.23828           58.4815979           1.60437584         0.00582388        0.08319831
 227        0.0          4782.23828           84.7051849           2.81444931         0.01021645        0.14594930
 228        0.0          4782.23828          110.238083            4.38927841         0.01593307        0.22761530
 229        0.0          4782.23828          128.914490            6.23091125         0.02261821        0.32311702
 230        0.0          4782.23828          142.048889            8.26018047         0.02998447        0.42834949
 231        0.0          4782.23828          148.200668           10.3773289          0.03766972        0.53813869
 232        0.0          4782.23828          152.240738           12.5521965          0.04556448        0.65092093
 233        0.0          4782.23828          156.436981           14.7870073          0.05367684        0.76681191
 234        0.0          4782.23828          158.371170           17.0494385          0.06188946        0.88413495
 235        0.0          4782.23828          159.013336           19.3210602          0.07013541        1.00193405
 236        0.0          4782.23828          159.174835           21.5949860          0.07838976        1.11985302
 237        0.0          4782.23828          159.656204           23.8757935          0.08666909        1.23812962
 238        0.0          4782.23828          159.656204           26.1565857          0.09494841        1.35640526
 239        0.0          4782.23828          159.975372           28.4419556          0.10324430        1.47491837
 240        0.0          4782.23828          159.975372           30.7273102          0.11154008        1.59342957
 241        0.0          4782.23828          159.975372           33.0126801          0.11983603        1.71194267
 242        0.0          4782.23828          159.975372           35.2980347          0.12813181        1.83045387
 243        0.0          4782.23828          159.975372           37.5834045          0.13642764        1.94896603
 244        0.0          4782.23828          159.975372           39.8687592          0.14472347        2.06747723
 245        0.0          4782.23828          159.975372           42.1541290          0.15301943        2.18599129
 246        0.0          4782.23828          159.975372           44.4394836          0.16131520        2.30450249
 247        0.0          4782.23828          159.975372           46.7248535          0.16961116        2.42301559
 248        0.0          4782.23828          159.975372           49.0102081          0.17790699        2.54152775
 249        0.0          4782.23828          159.975372           51.2955627          0.18620282        2.66003990
 250        0.0          4782.23828          159.975372           53.5809326          0.19449872        2.77855206
 251        0.0          4782.23828          159.975372           55.8662872          0.20279455        2.89706421
 252        0.0          4782.23828          159.975372           58.1516571          0.21109051        3.01557827
 253        0.0          4782.23828          159.975372           60.4369965          0.21938622        3.13408852
 254        0.0          4782.23828          159.975372           62.7223206          0.22768193        3.25259876
 255        0.0          4782.23828          159.975372           65.0076447          0.23597777        3.37111092
 256        0.0          4782.23828          159.975372           67.2929687          0.24427348        3.48962116
 257        0.0          4782.23828          159.975372           69.5782776          0.25256908        3.60812950
```

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FIGURE G-6
(Continued)

400-YEAR OUTPUT FORMAT

```
                                                                      70-YR             LIFETIME
 YEAR   LEACHATE(L)   CONSTITUENT (KG)   WELL CONCT (MG/L)   AVERAGE CONCT(MG/L)   RISK TO AN
-----   -----------   ----------------   -----------------   -------------------   INDIVIDUAL      NUMBER OF CASES
                                                                                   -----------     ---------------
 258        0.0          4782.23828          159.975372          71.8636017         0.26086479        3.72663879
 259        0.0          3927.90234          159.975372          74.1489258         0.26916051        3.84514809
 260        0.0             0.0              159.975372          76.4342499         0.27745622        3.96365738
 261        0.0             0.0              159.975372          78.7195740         0.28575206        4.08217049
 262        0.0             0.0              159.975372          81.0048981         0.29404777        4.20067978
 263        0.0             0.0              159.887421          83.2890015         0.30233896        4.31912613
 264        0.0             0.0              158.809891          85.5576935         0.31057435        4.43677425
 265        0.0             0.0              153.756424          87.7541809         0.31854761        4.55067635
 266        0.0             0.0              141.424438          89.7744904         0.32588136        4.65544701
 267        0.0             0.0              121.726379          91.5133820         0.33219343        4.74561882
 268        0.0             0.0               96.8089752         92.8963623         0.33721364        4.81733704
 269        0.0             0.0               70.7088013         93.9064636         0.34088033        4.86971569
 270        0.0             0.0               46.4007874         94.5693054         0.34328634        4.90408707
 271        0.0             0.0               28.7144470         94.9794617         0.34477526        4.92535877
 272        0.0             0.0               16.8274841         95.2198029         0.34564763        4.93782043
 273        0.0             0.0               11.0529604         95.3776703         0.34622073        4.94600964
 274        0.0             0.0                6.98499012        95.4774475         0.34658307        4.95118523
 275        0.0             0.0                3.19285393        95.5230408         0.34674841        4.95354652
 276        0.0             0.0                1.48947716        95.5442963         0.34682578        4.95465183
 277        0.0             0.0                0.93318778        95.5575867         0.34687376        4.95533562
 278        0.0             0.0                0.71453911        95.5677338         0.34691077        4.95586586
 279        0.0             0.0                0.31915778        95.5722656         0.34692705        4.95609951
 280        0.0             0.0                0.26214099        95.5760040         0.34694088        4.95629501
 281        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 282        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 283        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 284        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 285        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 286        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 287        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 288        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 289        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 290        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 291        0.0             0.0                0.0               95.5760040         0.34694088        4.95629501
 292        0.0             0.0                0.0               95.5689697         0.34691507        4.95592880
 293        0.0             0.0                0.0               95.5080872         0.34669417        4.95277214
 294        0.0             0.0                0.0               95.2906189         0.34590483        4.94149685
 295        0.0             0.0                0.0               94.8070831         0.34414971        4.91642284
 296        0.0             0.0                0.0               93.9716492         0.34111673        4.87309551
 297        0.0             0.0                0.0               92.7615967         0.33672458        4.81034756
 298        0.0             0.0                0.0               91.1868286         0.33100814        4.72868633
 299        0.0             0.0                0.0               89.3451996         0.32432270        4.63317871
 300        0.0             0.0                0.0               87.3159485         0.31695664        4.52795029
 301        0.0             0.0                0.0               85.1988220         0.30927145        4.41816044
 302        0.0             0.0                0.0               83.0239868         0.30137688        4.30538082
 303        0.0             0.0                0.0               80.7892151         0.29326475        4.18949413
 304        0.0             0.0                0.0               78.5268402         0.28505236        4.07217407
 305        0.0             0.0                0.0               76.2552338         0.27680647        3.95437622
 306        0.0             0.0                0.0               73.9813538         0.26855230        3.83646011
 307        0.0             0.0                0.0               71.7005463         0.26027292        3.71818066
 308        0.0             0.0                0.0               69.4197540         0.25199366        3.59990883
 309        0.0             0.0                0.0               67.1344299         0.24369794        3.48139858
```

FIGURE G-6
(Continued)

400-YEAR OUTPUT FORMAT

```
                                                                        70-YR          LIFETIME
  YEAR    LEACHATE(L)   CONSTITUENT (KG)   WELL CONCT (MG/L)  AVERAGE CONCT(MG/L)  RISK TO AN
                                                                                   INDIVIDUAL      NUMBER OF CASES
 -------  -----------   ----------------   -----------------  -----------------  --------------  ---------------
   310       0.0             0.0                 0.0              64.8491058       0.23540223        3.36288834
   311       0.0             0.0                 0.0              62.5638275       0.22710663        3.24438000
   312       0.0             0.0                 0.0              60.2784576       0.21881068        3.12586594
   313       0.0             0.0                 0.0              57.9934692       0.21051621        3.00737381
   314       0.0             0.0                 0.0              55.7081146       0.20222044        2.88886261
   315       0.0             0.0                 0.0              53.4227448       0.19392449        2.77034950
   316       0.0             0.0                 0.0              51.1373901       0.18562865        2.65183735
   317       0.0             0.0                 0.0              48.8520203       0.17733276        2.53332424
   318       0.0             0.0                 0.0              46.5666656       0.16903692        2.41481209
   319       0.0             0.0                 0.0              44.2812958       0.16074109        2.29630089
   320       0.0             0.0                 0.0              41.9959412       0.15244514        2.17778683
   321       0.0             0.0                 0.0              39.7105713       0.14414936        2.05927563
   322       0.0             0.0                 0.0              37.4252167       0.13585353        1.94076443
   323       0.0             0.0                 0.0              35.1398468       0.12755758        1.82225037
   324       0.0             0.0                 0.0              32.8544922       0.11926174        1.70373821
   325       0.0             0.0                 0.0              30.5691223       0.11096585        1.58522606
   326       0.0             0.0                 0.0              28.2837677       0.10267007        1.46671486
   327       0.0             0.0                 0.0              25.9983978       0.09437418        1.34820175
   328       0.0             0.0                 0.0              23.7130432       0.08607835        1.22969055
   329       0.0             0.0                 0.0              21.4276733       0.07778245        1.11117744
   330       0.0             0.0                 0.0              19.1423187       0.06948662        0.99266595
   331       0.0             0.0                 0.0              16.8569641       0.06119078        0.87415373
   332       0.0             0.0                 0.0              14.5716028       0.05289492        0.75564158
   333       0.0             0.0                 0.0              12.2874956       0.04460361        0.63719434
   334       0.0             0.0                 0.0              10.0187845       0.03636819        0.51954561
   335       0.0             0.0                 0.0               7.82226562      0.02839485        0.40564048
   336       0.0             0.0                 0.0               5.80192089      0.02106099        0.30087101
   337       0.0             0.0                 0.0               4.06297779      0.01474861        0.21069443
   338       0.0             0.0                 0.0               2.68001080      0.00972843        0.13897759
   339       0.0             0.0                 0.0               1.66988468      0.00606168        0.08659542
   340       0.0             0.0                 0.0               1.00701618      0.00365547        0.05222100
   341       0.0             0.0                 0.0               0.59681046      0.00216642        0.03094888
   342       0.0             0.0                 0.0               0.35641801      0.00129380        0.01848282
   343       0.0             0.0                 0.0               0.19851917      0.00072062        0.01029464
   344       0.0             0.0                 0.0               0.09873360      0.00035840        0.00512004
   345       0.0             0.0                 0.0               0.05312144      0.00019283        0.00275473
   346       0.0             0.0                 0.0               0.03184320      0.00011559        0.00165130
   347       0.0             0.0                 0.0               0.01851195      0.00006720        0.00095998
   348       0.0             0.0                 0.0               0.00830427      0.00003014        0.00043063
   349       0.0             0.0                 0.0               0.00374487      0.00001359        0.00019420
   350       0.0             0.0                 0.0               0.0             0.0               0.0
   351       0.0             0.0                 0.0               0.0             0.0               0.0
   352       0.0             0.0                 0.0               0.0             0.0               0.0
   353       0.0             0.0                 0.0               0.0             0.0               0.0
   354       0.0             0.0                 0.0               0.0             0.0               0.0
   355       0.0             0.0                 0.0               0.0             0.0               0.0
   356       0.0             0.0                 0.0               0.0             0.0               0.0
   357       0.0             0.0                 0.0               0.0             0.0               0.0
   358       0.0             0.0                 0.0               0.0             0.0               0.0
   359       0.0             0.0                 0.0               0.0             0.0               0.0
   360       0.0             0.0                 0.0               0.0             0.0               0.0
   361       0.0             0.0                 0.0               0.0             0.0               0.0
```

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relationships in a model run. The 400-year format provides the detailed information necessary for full analysis of a case; however, this format also requires eight pages of printout for every case.

The summary format, shown in Figure G-7, is sufficient for most cases. This format provides a one-line (reduced from 400-line) summary of each case. The summary gives the following information for each case: case number; specification of important input variables (climate, disposal type, exposure route, constituent, groundwater flow scenario, mobility class, and distance to exposure point); time to failure; clay layer and unsaturated zone time delays; total time to reach saturated zone; years of exposure (contamination at exposure point); year(s) of maximum exposure; maximum and average (based on number of years of contamination) constituent concentration at exposure point; maximum and average (based on 400 years) individual risk; total number of cases (summed over 400 years); and a brief designation of the toxic effect. The summary format is most useful in analysis of a large number of cases, and it is 200 times more efficient (in terms of printout volume) than the 400-year format. It preserves the most important data in the 400-year format and calculates three new values: average exposure point concentration, average individual risk, and total number of cases. It also conveniently displays the specified input variables. Nonetheless, the summary format is not always sufficiently informative, and the analysis of individual cases may require examination of the 400-year output format.

7. MAJOR ASSUMPTIONS IN THE LINER-LOCATION RISK MODEL

As in any predictive health risk model, there are numerous assumptions and simplifications incorporated into the liner-location risk model. The assumptions derive either from a lack of knowledge concerning the complex physical, chemical, and biological processes involved or from the necessity to simplify the model to make the analysis tractable. These assumptions must be recognized and taken into account by users of the model.

FIGURE G-7

SUMMARY OUTPUT FORMAT

```
                                                                                                     PAGE  30
                                          TIME DELAY (YEARS)     EXPOSURE (YEAR)      CONC.(MG/L)     INDIVIDUAL RISK
                                       -----------|---------- -------|-------     ---------|-------  ---------|-------
                                      |                    || TOTAL    MAX  ||                    ||                 |
CASE CL DISP.TYP RT  CONSTIT. SCENARIO FAIL  CLAY UNSAT TOTAL BEG END BEG END MAXIMUM AVERAGE AVERAGE MAXIMUM   CASES EFFECT
---- -- -------- --  -------- -------- ---- ----- ----- ----- --- --- --- --- ------- ------- ------- ------- ------- --------
 726  2 L.F VIIA GW  M. CHLOR B-1-60      3     0    20    23  27  68  44  50 0.6E+01 0.4E+01 0.6E-04 0.3E-03 0.3E+00 CANCER
 727  2 L.F VIIA GW  M. CHLOR C-1-60      3     0    20    23  24  50  26  47 0.2E+01 0.2E+01 0.2E-04 0.9E-04 0.9E-01 CANCER
 728  2 L.F VIIA GW  M. CHLOR D-1-60      3     0    20    23  24  49  25  47 0.2E+00 0.2E+00 0.2E-05 0.1E-04 0.1E-01 CANCER
 729  2 L.F VIIB GW  M. CHLOR B-1-60      3     0    21    24  28  70  45  52 0.5E+01 0.3E+01 0.5E-04 0.3E-03 0.3E+00 CANCER
 730  2 L.F VIIB GW  M. CHLOR C-1-60      3     0    21    24  25  52  27  49 0.1E+01 0.1E+01 0.1E-04 0.8E-04 0.8E-01 CANCER
 731  2 L.F VIIB GW  M. CHLOR D-1-60      3     0    21    24  25  51  26  49 0.2E+00 0.1E+00 0.1E-05 0.8E-05 0.8E-02 CANCER
 732  2 L.F I    GW  M. ISOBU B-1-60     75     0    61   136 140 282 157 265 0.4E-06 0.3E-06 0.0     0.0     0.0     KIDNEY
 733  2 L.F I    GW  M. ISOBU C-1-60     75     0    61   136 137 264 139 262 0.1E-06 0.1E-06 0.0     0.0     0.0     KIDNEY
 734  2 L.F I    GW  M. ISOBU D-1-60     75     0    61   136 137 263 138 262 0.1E-07 0.1E-07 0.0     0.0     0.0     KIDNEY
 735  2 L.F IA   GW  M. ISOBU B-1-60     28     0    25    53  57 246  74 229 0.2E-03 0.2E-03 0.0     0.0     0.0     KIDNEY
 736  2 L.F IA   GW  M. ISOBU C-1-60     28     0    25    53  54 228  56 226 0.5E-04 0.5E-04 0.0     0.0     0.0     KIDNEY
 737  2 L.F IA   GW  M. ISOBU D-1-60     28     0    25    53  54 227  55 226 0.5E-05 0.5E-05 0.0     0.0     0.0     KIDNEY
 738  2 L.F IIA  GW  M. ISOBU      N/A   NO
 739  2 L.F IIB  GW  M. ISOBU      N/A   NO
 740  2 L.F III  GW  M. ISOBU      N/A  150     0    65   215
 741  2 L.F IV   GW  M. ISOBU B-1-60     75     0    22    97 101 243 118 226 0.3E-03 0.3E-03 0.0     0.0     0.0     KIDNEY
 742  2 L.F IV   GW  M. ISOBU C-1-60     75     0    22    97  98 225 100 223 0.9E-04 0.9E-04 0.0     0.0     0.0     KIDNEY
 743  2 L.F IV   GW  M. ISOBU D-1-60     75     0    22    97  98 224  99 223 0.9E-05 0.9E-05 0.0     0.0     0.0     KIDNEY
 744  2 L.F VA   GW  M. ISOBU B-1-60     75     0    17    92  96 238 113 221 0.9E-03 0.8E-03 0.0     0.0     0.0     KIDNEY
 745  2 L.F VA   GW  M. ISOBU C-1-60     75     0    17    92  93 220  95 218 0.3E-03 0.3E-03 0.0     0.0     0.0     KIDNEY
 746  2 L.F VA   GW  M. ISOBU D-1-60     75     0    17    92  93 219  94 218 0.3E-04 0.3E-04 0.0     0.0     0.0     KIDNEY
 747  2 L.F VB   GW  M. ISOBU B-1-60     75     0    17    92  96 238 113 221 0.9E-03 0.8E-03 0.0     0.0     0.0     KIDNEY
 748  2 L.F VB   GW  M. ISOBU C-1-60     75     0    17    92  93 220  95 218 0.3E-03 0.3E-03 0.0     0.0     0.0     KIDNEY
 749  2 L.F VB   GW  M. ISOBU D-1-60     75     0    17    92  93 219  94 218 0.3E-04 0.3E-04 0.0     0.0     0.0     KIDNEY
 750  2 L.F VIIA GW  M. ISOBU B-1-60      3     0    20    23  27 241  44 224 0.5E-03 0.4E-03 0.0     0.0     0.0     KIDNEY
```

In keeping with traditional public health and EPA practice, simplifications and assumptions in the model are generally conservative (i.e., potential errors introduced by an assumption are likely to produce overestimates of the risk). Thus, it is likely that the risk estimates produced by the model are higher than actual risks rather than lower. For example, because of information gaps, many chemicals are assumed 100 percent persistent in groundwater, degradation prior to release is not considered, transverse dispersion in groundwater is not accounted for, and chemical removal by water treatment processes is neglected. Each of these assumptions is likely to cause risk overestimates.

The major assumptions contained in the liner-location risk analysis model are highlighted in Figure G-8. Specific assumptions within the failure/release, groundwater transport, and risk estimation components of the model are not exhaustively listed. These are covered in detail in Appendices A, B, and D, respectively. In addition, the simplifications made during the site-visit facilities waste and environment characterization are described in Appendices F, B, and C. Alternatives to some of these assumptions are being investigated in the ongoing model development.

FIGURE G-8

MAJOR ASSUMPTIONS IN THE LINER-LOCATION RISK ANALYSIS MODEL

Assumption/Simplification	Effect on Risk Estimate		
	Increases	Decreases	Either
Facility failure when probability exceeds 1%	X		
Release rate constant after failure		X	
Constituent release at water solubility concentration (free liquid not accounted for)			X
Clay delay based on entire theoretical liner adsorption capacity		X	
Wastestream or facility risks based only on constituents of concern		X	
No constituent degradation in facility prior to failure	X		
Constituent degradation in clay and unsaturated zone at same rate as in saturated zone	X		
No constituent biodegradation in the unsaturated zone	X		
Constituent transport in groundwater modeled using the median retardation factor for the constituent's mobility class			X
All exposure points directly downgradient from source	X		
Surface water concentration based on dilution only			X
Constant population, uniform age distribution, 70-year life span			X
Constituent removal by water treatment not included	X		
Model time horizons (200 years for release, 400 years for risk)		X	
Background chemical exposures not considered		X	

FIGURE G-8
(Continued)

MAJOR ASSUMPTIONS IN THE LINER-LOCATION RISK ANALYSIS MODEL

	Effect on Risk Estimate		
Assumption/Simplification	Increases	Decreases	Either
Failure/release model (see Appendix B)			
• Single probability and release volume representing all causes of failure			X
Groundwater transport model (see Appendix C)			
• Transverse dispersion neglected	X		
• Effects of pumping on aquifer not included		X	
Risk estimation model (see Appendix E)			
• Extrapolations from animal studies			X
• High to low dose extrapolations			X
• Upper 95% confidence level risk estimates for carcinogens	X		
• Based on one effect per chemical		X	
Waste/constituent characterization (see Appendix G)			
• Single parameter values for constituents (especially inorganics)			X
• Constituent mobility by class rather than continuous			X
Site exposure characterization (see Appendix D)			
• Potentially exposed populations approximated based on water supply records			X

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